# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**LIFE CYCLE COST ESTIMATE OF LSD(X)**

by

Allison Hills

June 2012

| | |
|---|---|
| Thesis Advisor: | Daniel Nussbaum |
| Second Reader: | Gregory Mislick |

**Approved for public release; distribution is unlimited**

THIS PAGE INTENTIONALLY LEFT BLANK

| REPORT DOCUMENTATION PAGE | | | *Form Approved OMB No. 0704-0188* |
|---|---|---|---|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503. | | | |
| **1. AGENCY USE ONLY *(Leave blank)*** | **2. REPORT DATE** June 2012 | **3. REPORT TYPE AND DATES COVERED** Master's Thesis | |
| **4. TITLE AND SUBTITLE** Life Cyle Cost Estimate of LSD(X) | | | **5. FUNDING NUMBERS** |
| **6. AUTHOR(S)** Allison Hills | | | |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** Naval Postgraduate School Monterey, CA 93943-5000 | | | **8. PERFORMING ORGANIZATION REPORT NUMBER** |
| **9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)** N/A | | | **10. SPONSORING/MONITORING AGENCY REPORT NUMBER** |
| **11. SUPPLEMENTARY NOTES** The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ______N/A__________. | | | |
| **12a. DISTRIBUTION / AVAILABILITY STATEMENT** Approved for public release; distribution is unlimited | | | **12b. DISTRIBUTION CODE** A |

**13. ABSTRACT (maximum 200 words)**

This thesis develops a model that provides a credible and reliable rough order magnitude (ROM) Life Cycle Cost Estimate (LCCE) for a newly constructed U. S. Navy Dock Landing Ship, LSD(X), over the various phases of design, procurement, and operations and support costs. The Systems Engineering Analysis (SEA) Curriculum at the Naval Postgraduate School (NPS) will use this estimate to help establish the costs of the proposed alternatives for LSD(X). This study also includes a cost benefit analysis through the comparison of LSD(X) to an alternative variant LSD(XB). The comparison examines how the baseline ROM LCCE of LSD(X) is affected by changes in technical parameters such as beam, number of LCACs, troop size, crew size and cargo capacity. Ultimately, this thesis provides a useful tool to aid decision makers in selecting the most cost effective alternative for the LSD(X) fleet for the expected 30 year operational period.

| | | | |
|---|---|---|---|
| **14. SUBJECT TERMS** LSD(X), life cycle cost estimate, ship construction costs, ship procurement | | | **15. NUMBER OF PAGES** 92 |
| | | | **16. PRICE CODE** |
| **17. SECURITY CLASSIFICATION OF REPORT** Unclassified | **18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified | **19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified | **20. LIMITATION OF ABSTRACT** UU |

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

**Approved for public release; distribution is unlimited**

**LIFE CYCLE COST ESTIMATE OF LSD(X)**

Allison M. Hills
Lieutenant, United States Navy
B.S., United States Naval Academy, 2004

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

from the

**NAVAL POSTGRADUATE SCHOOL**
**June 2012**

Author: Allison M. Hills

Approved by: Daniel A. Nussbaum
Thesis Advisor

Gregory Mislick
Second Reader

Robert F. Dell
Chair, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

# ABSTRACT

This thesis develops a model that provides a credible and reliable rough order magnitude (ROM) Life Cycle Cost Estimate (LCCE) for a newly constructed U.S. Navy Dock Landing Ship, LSD(X), over the various phases of design, procurement, and operations and support costs. The Systems Engineering Analysis (SEA) Curriculum at the Naval Postgraduate School (NPS) will use this estimate to help establish the costs of the proposed alternatives for LSD(X). This study also includes a cost benefit analysis through the comparison of LSD(X) to an alternative variant LSD(XB). The comparison examines how the baseline ROM LCCE of LSD(X) is affected by changes in technical parameters such as beam, number of LCACs, troop size, crew size and cargo capacity. Ultimately, this thesis provides a useful tool to aid decision makers in selecting the most cost effective alternative for the LSD(X) fleet for the expected 30 year operational period.

THIS PAGE INTENTIONALLY LEFT BLANK

## TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

# LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

# LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AAS | Amphibious Assault Ship |
| AOR | Auxiliary Oiler Replenishment |
| CBO | Congressional Budget Office |
| CER | Cost Estimating Relationship |
| CI | Confidence Interval |
| DAU | Defense Acquisition University |
| DoD | Department of Defense |
| FY | Fiscal Year |
| LCAC | Landing Craft Air Cushion (U.S. Navy) |
| LCCE | Life Cycle Cost Estimate |
| LHA | Landing Helicopter Assault (U.S. Navy) |
| LHD | Landing Helicopter Dock (U.S. Navy) |
| LPD | Landing Platform Dock (U.S. Navy) |
| LPH | Landing Platform Helicopter |
| LRIP | Low Rate Initial Production |
| LSD | Landing Ship Dock (U.S. Navy) |
| LSD (X) | Follow-on Landing Ship Dock (U.S. Navy) |
| LT | Long Tons |
| NATO | North Atlantic Treaty Organization |
| NCCA | Naval Center for Cost Analysis |
| O&S | Operations and Support |
| OPNAV | Office of the Chief of Naval Operations |
| $R^2$ | Coefficient of Determination |

| | |
|---|---|
| R&D | Research and Development |
| RAND | Research and Development Corporation (Santa Monica, CA) |
| RTO | Research and Technology Organization |
| ROM | Rough Order Magnitude |
| SAS | Systems Analysis and Studies |
| SCN | Ship Conversion Navy |
| SEA | Systems Engineering Analysis Curriculum at Naval Postgraduate School |
| SWBS | Ship’s Work Breakdown Structure |
| USN | United States Navy |
| WSARA | Weapons Systems Acquisition Reform Act (2009) |

THIS PAGE INTENTIONALLY LEFT BLANK

# EXECUTIVE SUMMARY


When determining the most cost effective shipbuilding programs, the U.S. Navy relies on Life Cycle Cost Estimates (LCCE) to evaluate the expected costs of a proposed system. These estimates are developed for each proposed system in order to aide decision makers in eliminating overly risky and costly programs and deciding between the remaining alternatives. In the early stages of an acquisition program, the LCCEs are developed on loosely defined parameters and must be robust to allow for changes in design specifications.

In the case of the Dock Landing Ship, LSD(X), the Office of the Chief of Naval Operations, OPNAV N8F, is determining the best possible means to maintain an LSD fleet able to meet the mission requirements in the distant future. Because the current LSD fleet is scheduled to be decommissioned over the next 20 to 30 years, mission capability gaps will become prevalent if not addressed. The Systems Engineering Analysis Curriculum students have been requested to delve into these capability gaps and develop a cost effective proposal that ensures that these gaps are not realized.

This thesis focuses on the proposal to build LSD (X) -- a new amphibious ship class to replace the current LSD ships. Because LSD (X) is in its design phase with little engineering data and specifications available, the appropriate cost estimating approach is to develop a model through parametric analysis. The Ships Work Breakdown Structure (SWBS) is used as a guide to develop materiel cost and labor hour estimates for specific sections of the proposed LSD(X). Using standard regression techniques, a number of parametric cost models were constructed at each of the nine SWBS levels based on historical amphibious ship procurement data. An aggregate cost model, combining the best performing models at each SWBS level, was then constructed to help determine the cost ramifications of adjustments in the ship's technical parameters. This cost model will be presented to the SEA Curriculum students to aid them in choosing the most cost effective means of meeting the requirements outlined in the capabilities-based assessment.

The aggregate cost model was then applied to the technical parameters assigned for LSD(X), as well as for a larger alternative variant LSD(XB), by the Systems Engineering Analysis curriculum students. After developing lead ship cost estimates, Monte Carlo Simulation was employed to identify the 80th percentile value of the LCCE Cumulative Distribution Function (CDF) in order to ensure compliance with the Weapons Systems Acquisition Reform Act of 2009.

After conducting 100,000 simulations, the 80th percentile lead ship estimates in FY12$ for LSD(X) and LSD(XB) are as follows:

- LSD(X) $660M
- LSD(XB) $829M

These estimates do not include design costs, and they include the construction cost of the lead ship only.

In order to generate the LCCE, the design costs, procurement costs, and the Operating and Support (O&S) costs for each ship must be considered. When these figures were calculated, the resulting LCCE for LSD (X) is $20.37 billion and $23.42 Billion for LSD(XB), in FY$12 dollars. Included in these LCCEs is the assumption that 11 new construction LSD ships will be purchased at an interval of one ship every other year over a 22 year time frame and that each ship will operate for 30 years.

THIS PAGE INTENTIONALLY LEFT BLANK

# ACKNOWLEDGMENTS

I would like to unreservedly thank the following people for helping me complete this thesis:

- My advisor Dr. Daniel Nussbaum: I am eternally grateful for your patience, guidance and support throughout this process. It has been an honor to work with you.
- My second reader LtCol Gregory Mislick, USMC, (Ret.): Thank you so much for tirelessly editing this document and turning it into a thesis.
- To Professor Samuel Buttrey: Thank you so much for sharing your knowledge and advice on dealing with uncooperative data.
- To LT Matt Martin, USN: I am so very grateful to have worked with you and your cost team. I wish you and your family "Fair Winds and Following Seas" on your next adventure.
- To my loving husband, David: I am so grateful for your love, support and encouragement. I only hope I can fill your shoes as you embark on a similar journey.
- To my three children: Jack, Mikey and Arabelle: You are my motivation and I thank God everyday for you. You make me very proud.
- To my parents: I would not be where I am today without your influence and support. I am so grateful to be your daughter.

THIS PAGE INTENTIONALLY LEFT BLANK

# I. INTRODUCTION

## A. PROJECT BACKROUND

The U.S. Navy currently has 12 operational Dock Landing Ships (LSD) designed to support amphibious operations worldwide. The first LSD of the Whidbey Island Class was commissioned in 1985 and was followed by the last of the Harper's Ferry Class in 1998. These LSDs are considered to be mid-life and because of the extensive time period required to develop and build a replacement follow-on LSD, the U.S. Navy, specifically OPNAV N8F of the Chief of Naval Operations (CNO) office, has requested a LSD fleet capabilities-based assessment. This assessment will focus on:

- Filling capability gaps (including improving declining materiel condition and readiness, replacing obsolete equipment, and reducing Total Ownership Costs)
- Developing designs that meet amphibious mission performance criteria, and
- Developing Life Cycle Cost Estimates (including Design costs, Procurement, and Operating and Support costs) of these designs.

As part of OPNAV N8F's request, an independent evaluation for LSD capabilities-based assessment to develop designs that meet amphibious mission performance criteria will be conducted by the Systems Engineering Analysis (SEA) curriculum students at the Naval Postgraduate School.

Embedded in the fleet recapitalization study is the need for a credible and reliable rough order of magnitude (ROM) life cycle cost estimate (LCCE) on the designs developed for the follow-on LSD. LCCEs are the expected costs associated with a particular program from "cradle to grave" including: Design, Procurement, and Operation and Support (O&S) costs. These estimates give decision makers the tools required to help with ship design and with the selection of the most cost effective alternative.

Ultimately, this thesis provides a useful tool to aid decision makers in selecting the most cost effective alternative for the LSD(X) fleet for the expected 30 year operational period.

## B. THESIS OBJECTIVE

This thesis develops a model that provides a credible and reliable rough order magnitude (ROM) Life Cycle Cost Estimate (LCCE) for a newly constructed LSD(X) over the various phases of design, procurement, and operations and support costs. The SEA Curriculum will use this model to estimate the costs of the proposed alternatives for LSD(X). This study also includes a cost benefit analysis through the comparison of LSD(X) to an alternative variant LSD(XB). The comparison examines how the baseline ROM LCCE of LSD(X) is affected by changes in technical parameters such as beam, number of LCACs, troop size, crew size and cargo capacity.

## C. METHODOLOGY OVERVIEW

Because very little specific information is known about the projected designs of the follow-on LSD, a ROM estimate classification, comprised of factored historical information, will be used in the LCCE.[1] The five common methods for developing cost estimates are estimates based on:

- Analogy
- Parametric Modeling
- Engineering or Build up Method
- Extrapolation by Actuals
- Expert Opinion

These methods permit the cost estimator to bridge the gap between historical data and future costs. The selection of the method depends on the current phase of the project, along with the statistical properties and logical relationships of the data.

[1] Naval Postgraduate School. *Unpublished Course Materiel for Course OA4702: Cost Estimation.* Naval Postgraduate School, 2012.

Because the follow-on LSD is in the concept and technology stage of development, both the Analogy and Parametric approaches are appropriate for use in the initial cost estimating process. An advantage to the Analogy approach would be that it is quick and therefore inexpensive to generate, but it is more uncertain because it is based on a single historical data point and reliant on a single system that is most analogous to the new system as its basis for comparison. The Parametric approach uses regression analysis to establish Cost Estimating Relationships (CERs). These CERs help estimate costs of designs which have specific system design parameters. Table 1 displays the definitions and appropriate usage of the Analogy and Parametric methods as well as the other three common cost estimating methodologies.

| Type | Definition | When Used | Method |
|---|---|---|---|
| Analogy | Forecasting the cost of a future weapon system or ship based on the historical cost of a similar or analogous item. | Early in the cost estimating process or when only one system to compare is available | An adjustment is applied to the cost of analogous system based upon chosen parameter metrics |
| Parametric | Establishes a statistically valid relationship among the dependent variables and/or various physical and performance characteristics. | System Development and Demonstration Phase | Apply statistical methods to the costs of two or more analogous systems. |
| Engineering/ Build-up | Detailed build-up of labor, materiel and overhead costs | Low Rate Initial Production (LRIP) | Estimate costs of discrete tasks and systems by lowest cost level and sum by Work Breakdown Schedule (WBS) |
| Extrapolation by Actuals | An extrapolation of current program costs | Late in Program during Low Rate Initial Production (LRIP) and Full Rate Productions | Use trends from current contract to estimate final system costs |
| Expert Opinion | One or more expert opinions provide the basis for the cost estimate | Used to support all types of estimating methodologies | Experts estimate parameter impacts along with impacts to labor and materiel costs |

Table 1. Description of Common Cost Estimating Methodologies (From Naval Postgraduate School Course OA4702: Cost Estimation)

Because of the early stage of the follow-on LSD project, a parametric approach is the most appropriate technique to create the LCCE. The parametric model uses statistical methods, like single and multi-variate regression to develop Cost Estimating Relationships (CERs) based on historical quantitative inputs. The model is able to capture major portions of an estimate given a restricted amount of data from similar platforms and provides decision makers with a platform to begin a cost benefit analysis process. Figure 1 depicts the appropriate use of modeling techniques to obtain estimates over the life of a program. Given the reasons previously mentioned, the parametric approach is useful in obtaining a ROM estimate due to the early concept phase of LSD(X).

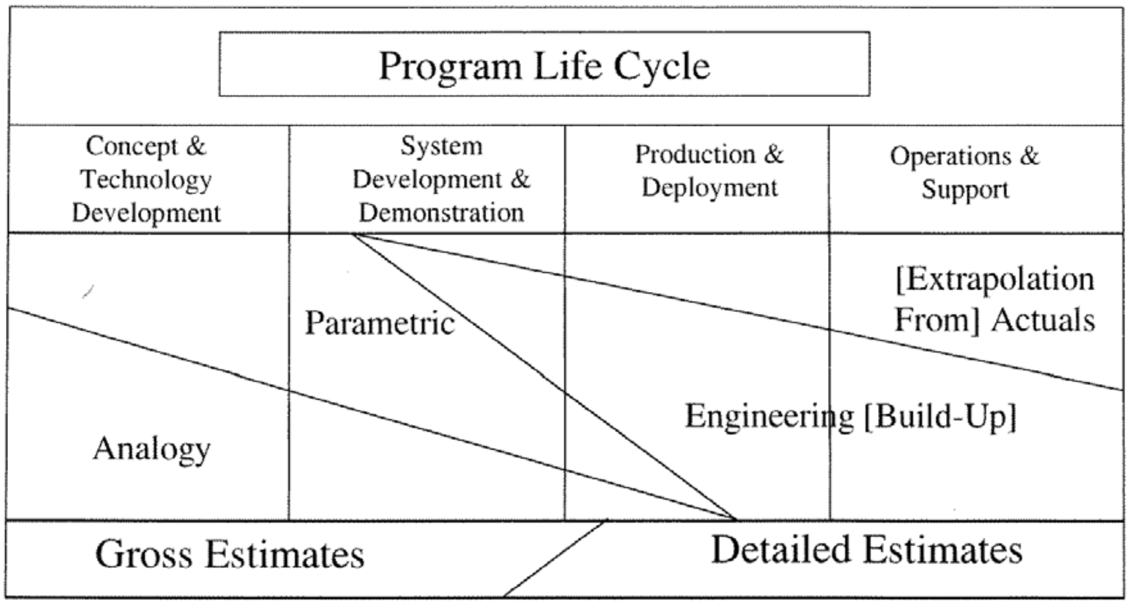


Figure 1. Depiction of the Appropriate Modeling Techniques Given Program Phase (From Naval Postgraduate School Course OA4702: Cost Estimation)

THIS PAGE INTENTIONALLY LEFT BLANK

# II. LITERATURE REVIEW

## A. U.S. NAVY AMPHIBIOUS FORCE

### 1. Mission

In the beginning of the 19th Century during the Peninsula War, the Duke of Wellington spoke of his success of his ground forces by stating “If anyone wishes to know the history of this war, I will tell them that it is our maritime superiority that gives me the power of maintaining my army while the enemy are unable to do so.” The United States has been involved in amphibious operations dating back as early as the American Revolution and continues to build a superior amphibious force. This amphibious force is capable of delivering and providing support for a Marine Expeditionary Unit at sea. Although the traditional mission revolves around sending a force ashore, a secondary mission of Humanitarian and Disaster Relief (HADR) has become increasingly important as well.

### 2. U.S. Navy Amphibious Ships

In order to better understand the factors that drive the LCCE of LSD(X), it is important to have a sound knowledge of the current amphibious fleet. There are presently three types of U.S. Navy Amphibious Warships, each with varying missions and capabilities. These three types are: Amphibious Assault Ships (LHA/LHD), Amphibious Transport Dock Ships (LPD), and Dock Landing Ships (LSD). Figure 2 denotes these three types.

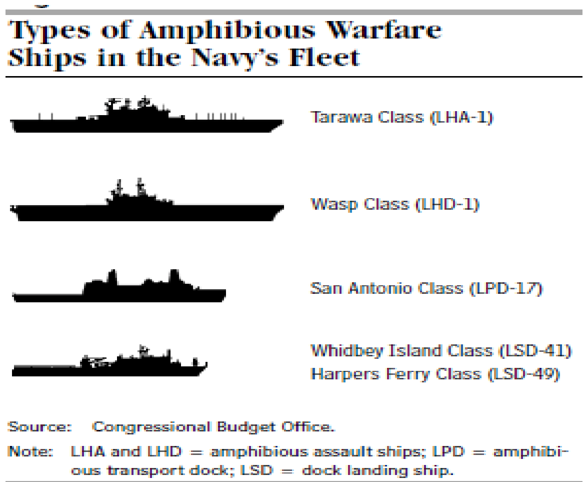


Figure 2. Types of Amphibious Warfare Ships (From Congressional Budget Office, 2011a)

The Amphibious Assault ships are typically analogous to light Aircraft Carriers in size. This group of ships includes the Wasp Class LHAs (Landing Helicopter Assault) and the Tarawa class LHDs (Landing Helicopter Dock). These ships are the centerpiece of the Amphibious Ready Group (ARG) or Expeditionary Strike Group (ESG) and are able to land and sustain forces on the ground during a time of hostility.[2]

Figure 3. LHA (left) and LHD (right), Amphibious Assault Ships (From Global Security Organization, 2012a and Jane's Fighting Ships, 2011)

The second group of amphibious warships is the Amphibious Transport Docks, also known as Landing Platform/Dock. The San Antonio LPDs fall under this category,

[2] Jane's Fighting Ships. *Amphibious Assault Ships.* Assessed October 12, 2011, http://www4.janes.com/.

with a main mission of transporting troops primarily via landing craft surface vessels and secondarily through helicopters. Designed as a multi-purpose ship, the LPDs are also often used for Humanitarian Assistance and Disaster Relief (HADR). The LPD does not have flag facilities and typically steams with an LHA/LHD and an LSD to comprise an ARG.

Figure 4. LPD: Amphibious Transport Dock/Landing Platform Dock (From Global Security Organization, 2011b)

The LSDs compose the Dock Landing Ship group of the Navy's amphibious force. The ships are designed to support amphibious operations via Landing Craft Air Cushion (LCAC), conventional landing craft and helicopters. As the first ship designed to embark and support four LCACs, the LSD-41 Whidbey Island class ship contributed a significant improvement in amphibious warfare.[3]

[3] Global Security Organization, *LSD 41*, Washington D.C. Assessed October 12, 2011. http://www.globalsecurity.org/military/systems/ship/lsd-41.htm


Figure 5. LSD: Dock Landing Ship (From Navysite.de, 2011)

The LSD fleet is well suited to carry out Humanitarian and Disaster Relief (HADR) operations and has done so as recently as Operation Tomodachi.[4] Operation Tomodachi assisted the country of Japan after the devastating earthquake and ensuing tsunami in March of 2011. The LSD is a multi-mission capable ship and it is evident that the future LSD(X) must continue to possess abundant war and peace time capabilities such as engaging in routine patrols overseas, reassuring allies, responding to crises and providing humanitarian aid.[5]

---

4 Commander US 7th Fleet. *Essex Embarks Japan Maritime Self-Defense Force Officer for Humanitarian Aid and Disaster Relief Coordination*, Assessed October 12,2011, http://www.c7f.navy.mil/news/2011/03-march/066.htm.

5 Congressional Budget Office. *An Analysis of the Navy's Amphibious Warfare Ships for Deploying Marines Overseas*. (Congressional Budget Office, Washington D.C., November 2011), 4.

## B. STUDIES THAT INCLUDE QUANTITATIVE ANALYSIS OF SHIP COST ESTIMATION

The following studies have been reviewed to provide a solid foundation from which to build on, but do not specifically address the limited scope of this thesis' principal research questions.

### 1. A Parametric Cost Model for Estimating Acquisition Costs of Conventional U.S. Navy Surface Ships

In his thesis, Loftus (1999) constructs ROM cost estimates based on historical data from 23 surface ships including small combatants, hydrofoils, cruisers, amphibious assault ships, oilers and support ships. His models predict the average procurement costs of a U.S. Naval surface ship by using the ship light displacement, the ship overall length, the ship propulsion shaft horsepower, and the number of propulsion engines as inputs.

Loftus' models only generate rough estimates with coefficients of variation between 74% and 83%; therefore the predictions may overestimate or underestimate the actual cost by more 74%. His estimates are intended to provide answers where limited data and/or engineering plans were available.

Loftus concludes that parametric models are appropriate for the production of verifiable cost estimates to be utilized to aid decision makers in determining expected program acquisition costs.

### 2. An Application of Data Mining Algorithms for Shipbuilding Cost Estimation

The North Atlantic Treaty Organization (NATO) Research and Technology Organization (RTO) Systems Analysis and Studies (SAS) Task group completed this study in 2011 in order to generate two independent cost estimates on the development and construction costs of the Royal Netherlands Navy Rotterdam class ships. The two methods used to produce cost estimates are the parametric approach and the analogy approach.

The parametric approach utilized the M5 model tree algorithm which included the combination of decision trees and linear regression models. The analogy approach is based on hierarchical cluster analysis and non-linear optimization. In order to analyze the results produced by these two different approaches, a database was constructed to include characteristics from 57 ships in 16 classes from six nations to include: Amphibious Assault Ships (AAS), Auxiliary Oiler Replenishment (AOR), Landing Platform Dock (LPD), Landing Platform Helicopter (LPH), Dock Landing Ship (LSD) and Icebreaker class ships.

After producing the cost estimates based on the cost and physical characteristics of the ships in the database, Kaluzny compares the estimates to the actual cost of Royal Netherlands Navy Rotterdam class ships. Kaluzny concludes that both methods are appropriate for providing accurate estimates and recommends that these methods should be considered for generating production estimates for future amphibious ships

## C. CHALLENGES OF LSD(X) RECAPITILIZATION STUDY

### 1. Ship Procurement Rising Costs

In 2005, Congress requested that the RAND Corporation quantify the reason that ships costs were increasing at nearly double the rate of consumer inflation. The RAND report concluded that the growth in cost is equally split between economy-driven and customer-driven factors.[6] The Navy only has control over the factors related to design complexity and requirements. In order to reduce the costs of the vessels desired, the Navy must "limit the growth in requirements and features of its ships."[7] The RAND Corporation report also studied the relationship between shipbuilders and cost escalation. By making improvements in efficiency and reductions in indirect costs, shipbuilders can play a role in decreasing the cost escalation of Naval Warships.[8]

[6] RAND Corporation, *Why Has the Cost of Navy Ships Risen?* (RANDCorp., Santa Monica, CA, 2006), 21.

[7] RAND Corporation, *Why Has the Cost of Navy Ships Risen?* (RANDCorp., Santa Monica, CA, 2006), 59.

[8] RAND Corporation, *Why Has the Cost of Navy Ships Risen?* (RANDCorp., Santa Monica, CA, 2006), 71.

### 2. Meeting Demand given Fiscal Constraints

In order to meet the demand required by the Navy's combatant commanders, the proposed FY 2012 shipbuilding plan includes a timeline for amphibious ship procurement through 2041. The plan was analyzed by the Congressional Budget Office and a report was presented with the conclusion that the Navy would fall below the thirty ship objective during the following time periods: 2012–2016 and 2032–2041. Figure 6 presents this inventory issue utilizing the projected FY 2012 naval shipbuilding plan. If fewer ships are available and the usage demand remains the same, the ships utilized will experience a higher operational tempo and the associated costs will increase. These costs include: maintenance, fuel, and increased sea pay for the sailors.[9] These complex scenarios and factors must be considered into the design and procurement of LSD(X) and will remain a challenge for the SEA department conducting the assessment.

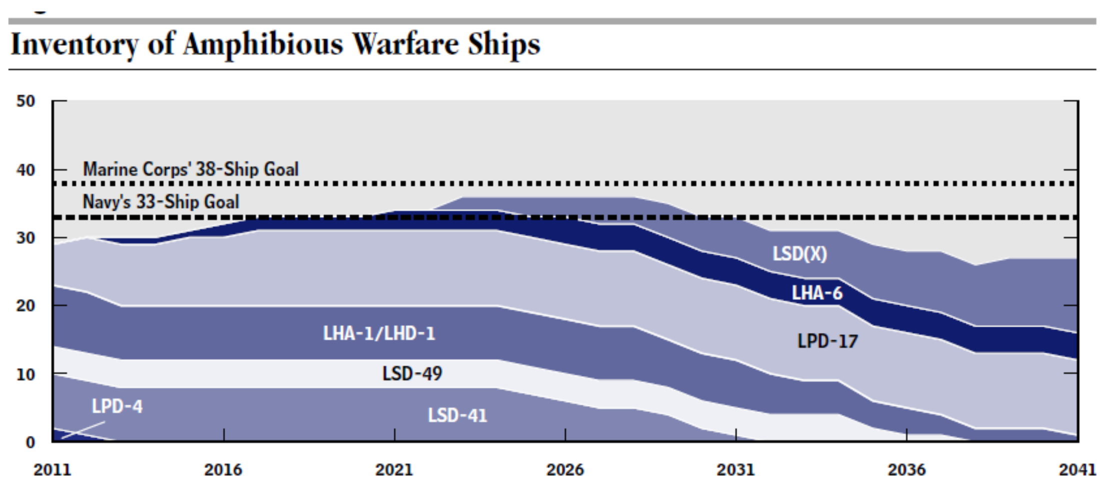


Figure 6. Projected Inventory of Amphibious Ships through FY2041 (From Congressional Budget Office, 2011b)

---

9 Congressional Budget Office. *An Analysis of the Navy's Amphibious Warfare Ships for Deploying Marines Overseas* (Congressional Budget Office, Washington D.C., November 2011), 9.

THIS PAGE INTENTIONALLY LEFT BLANK

# III. METHODOLOGY

This chapter describes the parametric cost estimation approach utilized to turn raw cost and technical data into quantitative predictions. These cost estimates will be utilized by the SEA department to aid decision makers as to the best possible development of LSD(X). Chapter III describes the data set and the specific procedures and decisions required to produce an appropriate model to utilize in the estimation of LSD(X).

## A. COLLECTING AND PROCESSING THE DATA SET

### 1. Cost Data

The cost data set compiled includes procurement cost and labor data for five amphibious warships: USS America (LHA 6), USS Wasp (LHD 1), USS Whidbey Island (LSD 41), USS Harpers Ferry (LSD 49) and the USS San Antonio (LPD 17). Each of these warships is considered a lead warship because she was the first ship built in her class. The data for each warship is divided into nine levels referred to as the Ships Work Breakdown Structure (SWBS). The SWBS is often used as a method to separate all components of a ship into groups based on function. Table 2 displays the Navy's description of SWBS at the one digit level. The one digit level SWBS for a ship is the most basic and is therefore appropriate to build a ROM estimate. As the design phase progresses, a two or three digit SWBS should be used to develop a more thorough cost estimate as further subsystems are examined.

The data set includes the costs of materiels associated with each one digit SWBS level, the number of man hours utilized to produce each SWBS level, and a weight associated with SWBS levels 100–700. Levels 800 and 900 are not measured in terms of weight and are typically estimated as a percentage of SWBS 100–700. [10]

[10] Naval Sea Systems Command Cost Engineering and Industrial Analysis Group. *Overview of Cost Estimating*. Naval Sea Systems Command Unpublished Presentation, 2008.

| Ships Work Breakdown Structure (SWBS) Definitions | | |
|---|---|---|
| 100 | Hull Structure | Shell plating, decks, bulkheads, framing superstructure, pressure hulls & foundations |
| 200 | Propulsion Plant | Boilers, reactors, turbines, gears, shafting propellers, steam piping and lube oil piping |
| 300 | Electric Plant | Ship service power generation equipment, power cable, lighting systems, & emergency electrical systems |
| 400 | Command & Surveillance | Navigation systems, interior communication systems, fire control systems, radars, sonars, radios, telephones, and command & control systems |
| 500 | Auxiliary Systems | Air conditioning, ventilation, refrigeration, replenishment at sea systems, anchor handling, elevators, fire extinguishing systems, distilling plants, steering systems, and aircraft launch and recovery systems |
| 600 | Outfit and Furnishing | Hull fittings, painting, insulation, berthing, sanitary spaces, offices, medical spaces, ladders, storerooms, laundry & workshops. |
| 700 | Armament | Guns, missile launchers, ammunition handling and stowage torpedo tubes, depth charges, mine handling and stowage, small arms |
| 800 | Integration/Engineering | Recurring engineering |
| 900 | Ship Assembly & Support Services | Staging, scaffolding, launching, trials, temporary utilities and services, materiel handling and removal services, and cleaning services. |

Table 2. NAVSEA SWBS Breakdown (From Naval Postgraduate School Course OA4702: Cost Estimation)

The sources of data were culled from a NAVSEA database that includes the details described above producing a 45 by 3 matrix. The 45 rows each contain the 100–900 SWBS level for each of the five amphibious lead ships. The three columns contain data related to the weight in Long Tons (LT), the Materiel Cost ($) and the Labor Hours (hrs) required to build each SWBS Level. Because the database utilized contains proprietary information, only the heading will be given in Table 3 in order to help provide a visual basis of the data. Table 3 shows only one row of the five amphibious ships, namely USS America (LHA-6) using XXs to denote the proprietary data. The data provided for this ship is the weight, materiel cost and man hours for each of the nine one-digit SWBS Levels.

| LHA-6 (SWBS Level) | Weight (LT) | Materiel Cost ($) | Labor Hours (Hrs) |
|---|---|---|---|
| 100 Hull Structure | XX LT | X.X Million | X.X Million Hrs |

Table 3. Example of Data Set using the Lead Ship USS America Class (LHA-6)

### 2. Technical Data

The data set also includes technical parameters and attributes for each of the five classes of amphibious warships. These parameters were obtained from various publicly available sources. The lead ships included in the data set are summarized in Table 4. By developing a model that considers the impact of displacement, length, beam, draft, crew size, troop size, number of LCACs and cargo capacity of each ship, this thesis provides the SEA team with a method of testing the sensitivity of the cost estimate by varying these values they deem necessary to produce the ship that best meets the recapitalization requirements.

| | Amphibious Ship | Displacement (LT) | Length (ft) | Beam (ft) | Draft (ft) | Crew Size | Troop Size | # LCAC | Cargo Capacity (Cubic Feet) |
|---|---|---|---|---|---|---|---|---|---|
| 1. | LHA-6 | 40687.5 | 844.16 | 193.9 | 28.54 | 1124 | 1687 | 0 | 160000 |
| 2. | LHD-1 | 36876.79 | 847.11 | 140.09 | 26.57 | 1188 | 1687 | 3 | 125000 |
| 3. | LPD-17 | 23482.14 | 683.73 | 104.66 | 22.97 | 388 | 720 | 2 | 34000 |
| 4. | LSD-41 | 14459.82 | 609.58 | 84 | 20.67 | 434 | 402 | 4 | 5000 |
| 5. | LSD-49 | 15186.61 | 609.58 | 84 | 20.67 | 434 | 402 | 2 | 67600 |

Table 4. Amphibious Ship Technical Specifications After Doehring, 2012 and Jane's Fighting Ships, 2011

The final data set has been expanded to include the above technical specifications, making it a 45 by 11 matrix. Each of the five lead ships is broken down into nine level SWBS providing 45 rows (5*9). The 11 columns account for the eight technical parameters mentioned above and the inclusion of the weight, labor hours, and materiel cost data.

## B. NORMALIZING THE DATA SET

In order to develop parametric cost estimates that rely on regression analysis, each data point must be carefully evaluated and properly adjusted for inflation. This inspection is necessary because the data set consists of a variety of ship classes, constructed over the past three decades.

### 1. Standardizing Units of Measurement and Definitions

For the purpose of this thesis, the following definitions are standardized as follows:

- Displacement, measured in Long Tons, is the full load weight of the vessel when it is loaded to maximum capacity. The measurement includes the weight of the ship and its cargo, personnel, fuel, water, stores and other items necessary for use on a transit.
- Length, measured in feet, is the overall length measured from the extreme forward end of the bow to the extreme stern.
- Beam, measured in feet, is the width of the ship at its widest point.
- Draft, measured in feet, is the vertical distance between the waterline and the bottom of the hull while the ship is in its fully loaded configuration.
- Crew Size refers to the number of personnel the ship was designed to accommodate in order to effectively man the ship to conduct all required missions.
- Troop Size refers to the number of Marines the ship was designed to transport. This size does not include the number of Marines the ship can transport in a surge capacity.
- Number of LCACs refers to the number of Landing Craft Air Cushions that may be transported on the vessel.
- Cargo Capacity, measured in cubic feet, refers to the amount of designated cargo storage on board the vessel.

### 2. Inflation Normalization

To normalize all dollar values for inflation, individual dollar amounts are converted into FY2012 dollars utilizing the Joint Inflation Calculator (development version 1c FY 2012). The Joint Inflation Calculator was developed by the Naval Center for Cost Analysis to provide inflation rates and indices for the Department of Defense. The JIC is publically available and may be downloaded from the Naval Center for Cost Analysis (NCCA) website at www.ncca.navy.mil. The inflation category selected for the appropriate normalization of figures in this thesis was SCN, or Shipbuilding and

Conversion, Navy. The proprietary data displayed in the example provided in Table 3 has been converted by these inflation indices to the final set of data which are used in the subsequent analysis.

### 3. Ship Quantity Normalization

As more ships of the same class are produced in the shipyard, the labor force becomes more experienced and the subsequent ships built become less costly. This theory is called learning. Learning is only applied to the production labor in the SWBS 100–700 groups.[11] Because the data set includes ships from classes with a varying number of ships in each class, only the lead ship production costs are used in order to predict the cost of the lead LSD (X) ship.

## C. CONSTRUCTING THE MODEL

Now that the data set has been compiled and adjusted to account for inflation and quantity, data analysis can be used to identify relationships between cost data and technical attributes of the warships. The regression techniques used to develop a model for predicting the cost of LSD (X) are explained in the following sections.

### 1. Relationship Determination and Transformation

The first step is to employ linear regression techniques to the data set in order to determine if a linear relationship exists between the dependent variable and an independent variable(s). Often the relationship is non-linear and a transformation of the variables is applied to increase the statistical significance of a relationship. Transforming a variable involves using a mathematical operation to change its measurement scale. The transformations commonly applied to variables to determine if a non-linear relationship exists are the logarithmic, exponential and the power functions.

[11] Naval Sea Systems Command Cost Engineering and Industrial Analysis Group. *Overview of Cost Estimating.* Naval Sea Systems Command Unpublished Presentation, 2008.

### 2. Regression Model Generation

In order to build parametric cost models for LSD(X), the Analysis ToolPak add-in feature for Excel 2007 was used as the main regression tool to conduct Ordinary Least Squares (OLS) regression. OLS minimizes the sum of squared vertical distances between the actual responses and the predicted responses of the linear approximation.

Additional independent variables may be added in pursuit of a better model than the model resulting from single variable regression. These additional variables must not be too highly correlated in order to avoid the ramifications of multi-collinearity.

### 3. Model Determination

The goal is to produce a functional relationship between the dependent variables-materiel costs and labor hours-and one or more of the independent technical variables. In order to measure the goodness of fit of these models, the values for "P-value," and "Adjusted $R^2$" produced in the Full Model Report in Excel will be analyzed, using the statistical textbook by Devore as a reference[12]. These statistics provide insight as to whether or not variables should be included in a model.

#### *a. P-Value*

The p-value statistic is a measure of evidence against the null hypothesis. The null hypothesis is "the factors added to the model have no influence over the dependent variables, materiel cost and labor hours." If the null hypothesis is correct, then the materiel cost or labor hours of the LSD(X) can be better predicted by the average of the historical cost data than by the technical variables introduced. For example, when building the cost model for the materiel costs associated with the 100 SWBS level (Hull Structure), one null hypothesis to be tested is that one of the eight technical parameters (Length, Displacement, Beam, Draft, Crew Size, Troop Size, Cargo Capacity and number of LCACs) will have no influence on predicting the materiel cost of the hull structure. Because this is the null hypothesis, it must be overturned by statistical significance for it

[12] Jay Devore. *Probability and Statistics for Engineering and the Sciences* 7th Edition. Brooks/Cole, 2007.

to be disputed. A similar null hypothesis will be created for each technical factor given both labor hours and materiel cost as separate dependent variables. For a single factor model using Beam as the regressor, the model is:

$$\text{Materiel Cost (\$)} = \beta_0 + \beta_1 * \text{Beam (ft)}$$

The hypothesis can be displayed as:

$H_0$ (Null Hypothesis): $\beta_1 = 0$ (cost is not related to size of beam)

$H_A$ (Alternative): $\beta_1 \neq 0$ (cost is related to size of beam)

When an Analysis of Variance (ANOVA) test is conducted, the p-value produced can be interpreted as the probability that the coefficients of the independent variables in the model are all zero. The significance level, α, is selected as a measure for determining which variables will be allowed into the model. For the purpose of this thesis we have selected an α of 0.1 to determine whether or not we accept the null hypothesis. If the P-value is ≤ 0.1, we will reject the null hypothesis. If the P-value is >0.1, we will not reject the null hypothesis.

For the materiel cost versus beam model above, the excel output is provided in Figure 7. We note that the P-value (highlighted) is well below our alpha of 0.1. In this case we reject the null hypothesis that cost is not predicted by the size of the beam, and we conclude that the size of the beam of the LSD (X) will affect the materiel cost.

ANOVA

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 1 | 3.32E+15 | 3.32E+15 | 27.99581 | 0.013171177 |
| Residual | 3 | 3.56E+14 | 1.19E+14 | | |
| Total | 4 | 3.68E+15 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* |
|---|---|---|---|---|---|---|---|---|
| Intercept | -4.4E+07 | 15002894 | -2.95663 | 0.059705 | -92103898.68 | 3387908.6 | -9.2E+07 | 3387909 |
| Beam..ft. | 618782.4 | 116947.6 | 5.291107 | 0.013171 | 246602.8496 | 990961.961 | 246602.8 | 990962 |

Figure 7. ANOVA Output for Beam

### *b. Coefficient of Determination, $R^2$*

The coefficient of determination ($R^2$) evaluates the fit of the cost models created with regression. $R^2$ is a ratio of the explained variation to the total variation. An $R^2$ value of zero describes a model in which none of the variation in the model can be explained by the regressor(s) used. An $R^2$ value of 1 describes a regression model that fits perfectly and all variation can be attributed to the regressor(s) used in the construction of the model. The coefficient of determination can be calculated as:

$$R^2 = \frac{\text{explained variation}}{\text{total variation}} = \frac{\sum (Y_{est} - \bar{Y})^2}{\sum (Y - \bar{Y})^2}$$

where **Y** are the observed values for the dependent variable, $\bar{Y}$ is the average of the observed values and $\mathbf{Y}_{est}$ are predicted values for the dependent variable using the regression equation[13]. For the purpose of this thesis, we determined that a $R^2$ value of 0.7 will be required for acceptance as a valid model.

### *c. Mean, Standard Deviation and Confidence Interval*

For the case when a linear regression model does not meet our criteria of 0.7 $R^2$ and a p-value $\leq 0.1$, the mean and standard deviation of historical materiel costs or labor hours can be used for the cost or labor estimates and to construct a confidence interval around those estimates. The mean and standard deviation can be calculated by using the following formulas[14]:

*Mean:* $$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

*Where the sample consists of n observations*

---

[13] Jay Devore. *Probability and Statistics for Engineering and the Sciences* 7th Edition. Brooks/Cole, 2007

[14] Jay Devore. *Probability and Statistics for Engineering and the Sciences* 7th Edition. Brooks/Cole, 2007

*Sample Standard Variance:* $$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

*Where the sample consists of n observations*

*Sample Standard Deviation:* $$S = \sqrt{S^2}$$

The standard deviation is used to help create confidence intervals around the mean using the t- distribution. The t- distribution is a continuous probability distribution that arises when estimating the mean of a normally distributed population in situations where the sample size is small. The critical value, t, can be found using a t-table using an appropriate alpha and n-1 degrees of freedom. Using the definitions for the mean (μ) and standard deviation (s) provided, the confidence intervals will be produced using the following formula[15]:

*Confidence interval for μ:* $(\bar{X} - t_{\alpha/2,\, n-1}\, s / \sqrt{n},\ \bar{X} + t_{\alpha/2,\, n-1}\, s / \sqrt{n})$

## 4. Transformations to Achieve Linearity

Not all data sets are linear. Many of those that contain non-linear data can be transformed to make the data linear in order to perform regression analysis and establish the slope and intercept of the original data set while discovering relationships that may exist between the dependent and independent variables. Transformations are often applied when the data ranges over several orders of magnitude.[16] For the purpose of this thesis, the Exponential, Logarithmic and Power models will be used in addition to the simple linear regression model. The Transformations of the variables are provided in Table 5.

---

[15] Devore, Jay. *Probability and Statistics for Engineering and the Sciences* 7th Edition. Brooks/Cole, 2007

[16] Kaluzny, An application of Data Mining Algorithms for Shipbuilding Cost Estimation, (Defence Research & Development Canada Centre for Operational Research & Analysis, Ottawa, CA,2011), 4.

| Method | Transformation(s) | Regression equation | Predicted value ($\hat{y}$) |
|---|---|---|---|
| Standard linear regression | None Needed | $y = b_0 + b_1x$ | $\hat{y} = b_0 + b_1x$ |
| Exponential model | Dependent variable = log(y) | $\log(y) = b_0 + b_1x$ | $\hat{y} = 10^{b_0 + b_1x}$ |
| Logarithmic model | Independent variable = log(x) | $y= b_0 + b_1\log(x)$ | $\hat{y} = b_0 + b_1\log(x)$ |
| Power model | Dependent variable = log(y)<br>Independent variable = log(x) | $\log(y)= b_0 + b_1\log(x)$ | $\hat{y} = 10^{b_0 + b_1\log(x)}$ |

Table 5. Transformations to Achieve Linearity

THIS PAGE INTENTIONALLY LEFT BLANK

# IV. COST ANALYSIS

## A. SINGLE VARIABLE REGRESSIONS

Our data analysis begins by determining if a relationship exists between materiel cost or labor hours and any of the eight individual technical parameter variables for each SWBS level. Each of the proposed models are transformed logarithmically, exponentially, and by using the power function as described in the previous section. Approximately 600 models are created and either rejected or accepted given the criteria outlined in Methodology chapter. If the model meets acceptance criteria (p-value $\leq 0.1$ and $R^2 \geq 0.7$) the regressor coefficients are recorded in the aggregate cost model. This process is repeated for all single variable regression models.

Of the 600 models created, Table 6 provides the 23 models remaining that meet the criteria outlined in the steps mentioned above. We accept at least one model for every SWBS level. Many of the SWBS levels have more than two models that may be appropriate for predicting the cost of LSD(X).

| SWBS Level | Model | Factor | P-Value | $R^2$ |
|---|---|---|---|---|
| 100 | Linear | Beam | 0.01 | 0.9 |
| 100 | Linear | Draft | 0.04 | 0.82 |
| 100 | Power | Crew | 0.03 | 0.83 |
| 200 | Linear | Beam | 0.0532 | 0.76 |
| 200 | Linear | Cargo | 0.1 | 0.65 |
| 300 | Linear | Beam | 0.01 | 0.9 |
| 300 | Power | Crew | 0.04 | 0.79 |
| 300 | Linear | Draft | 0.06 | 0.75 |
| 400 | Exp | Length | 0.03 | 0.85 |
| 400 | Exp | Troops | 0.03 | 0.84 |
| 400 | Exp | Crew | 0.04 | 0.8 |
| 500 | Log | Crew | 0.02 | 0.88 |
| 500 | Linear | Draft | 0.0346 | 0.82 |
| 500 | Linear | Beam | 0.02 | 0.87 |
| 600 | Linear | Beam | 0.0384 | 0.81 |
| 600 | Linear | Cargo | 0.09 | 0.68 |
| 600 | Linear | Draft | 0.09 | 0.67 |
| 700 | Linear | LCAC | 0.03 | 0.85 |
| 700 | Power | Cargo | 0.06 | 0.74 |
| 800 | Linear | Beam | 0.1305 | 0.65 |
| 900 | Lin | Beam | 0.002 | 0.98 |
| 900 | Exp | Displacement | 0.02 | 0.86 |
| 900 | Exp | Draft | 0.02 | 0.89 |

Table 6. Acceptable Models from Single Variable Regression with Materiel Cost as Dependent Variable

Table 7 provides the results from running the same single variable regression given labor hours as the dependent variable. Because none of the regression models in the 200, 400, 500 and 700 SWBS levels met the required acceptance criteria, the mean and standard deviations will be used to develop an appropriate labor hour estimates for these SWBS levels.

| SWBS Level | Model | Factor | P-Value | R^Squared |
|---|---|---|---|---|
| 100 | pwr | disp | 0.06 | 0.75 |
| 100 | pwr | troops | 0.09 | 0.67 |
| 100 | pwr | draft | 0.09 | 0.67 |
| 300 | log | disp | 0.01 | 0.91 |
| 300 | log | draft | 0.01 | 0.9 |
| 300 | log | Beam | 0.02 | 0.89 |
| 600 | Power | Disp | 0.07 | 0.71 |
| 600 | Power | Troops | 0.1 | 0.65 |
| 800 | log | crew | 0.01 | 0.91 |
| 800 | linear | Troops | 0.05 | 0.77 |
| 800 | linear | len | 0.07 | 0.73 |
| 900 | log | Disp | 0.01 | 0.9 |
| 900 | log | Draft | 0.02 | 0.86 |
| 900 | log | Troops | 0.02 | 0.86 |

Table 7. Acceptable Models from Single Variable Regression with Labor Hours as Dependent Variable

## B. MULTI-VARIATE REGRESSIONS

After completing single variable regression, multi-variate regression is the next step in developing our cost model. Prior to performing multi factor regression, a multi-collinearity test is conducted to determine how highly correlated the technical parameter variables are to each other. The existence of multi-collinearity can have several negative effects[17] of the results of linear regression:

- The standard deviation of regression coefficients is inflated, therefore lowering the significance of the coefficients.
- The effects of each independent variable on predicting the outcome of materiel costs or labor man-hours may become difficult to interpret.

[17] Naval Postgraduate School. *Unpublished Course Materiel for Course OA4702: Cost Estimation*. Naval Postgraduate School, 2012.

- A high overall $R^2$ value may be produced when non-significant correlated variables are present in the model, giving us false confidence in the predictive capability of the model.

To detect multi-collinearity between the eight technical ship parameters, we use the Correlation function in Excel. The results from this computation are displayed in Table 8. Unfortunately, all factors are highly correlated (.86 or higher) with the exception given to the number of LCACs per ship parameter.

A scatterplot matrix was also produced by using the Multi-Variate Correlation function in JMP statistics software (version JMP Pro 9) and is provided in Figure 8. The scatterplot matrix visually displays the correlation amongst the regressors. Because the technical parameters are all somewhat related to the overall size of the ship, a strong relationship exists between the variables, except for the "# of LCAC" variable. For example, as the length of a ship is increased, we can expect the beam and displacement to also increase. This idea is intuitive and in the case of this thesis, all independent variables used to produce the models are related to overall size of the ship.

The preferred method to remedy the multi-collinearity issue is through the inclusion of more data points. The addition of data points would produce more precise parameter estimates by lowering the standard errors produced by the regression analysis in small samples. Unfortunately, additional data was not available; therefore, the method of combining independent variables was attempted. Multiple variable combinations were input into the model in an attempt to reduce the correlation among the variables. For example: length and beam were multiplied to create a new variable called LENBEAM. After iterating through many of these combinations, it became clear that combining variables would not lower the correlation factor to an acceptable status of 0.7 or below. In addition, the combinations were complex and would not provide the SEA Curriculum students with an appropriate method for determining which dependent variable would have the greatest effect on cost. Because of these issues, multi-variate regression was deemed unacceptable for producing models to determine materiel cost and labor hours at each SWBS level.

| | Disp | Length | Beam..ft. | Draft..ft. | Crew | Num Troops | #LCAC | Cargo Cap |
|---|---|---|---|---|---|---|---|---|
| Disp. | 1 | | | | | | | |
| Length | 0.99175 | 1 | | | | | | |
| Beam..ft. | 0.94797 | 0.907804 | 1 | | | | | |
| Draft..ft. | 0.995769 | 0.97866 | 0.972797 | 1 | | | | |
| Crew | 0.927846 | 0.953627 | 0.861131 | 0.918464 | 1 | | | |
| Num Troops | 0.98876 | 0.998316 | 0.912836 | 0.977814 | 0.968655 | 1 | | |
| #LCAC | -0.57877 | -0.48019 | -0.72728 | -0.61992 | -0.37696 | -0.47662 | 1 | |
| Cargo Cap | 0.896342 | 0.882336 | 0.897491 | 0.900568 | 0.905064 | 0.896737 | -0.69514 | 1 |

Table 8. Correlation Among Regressors

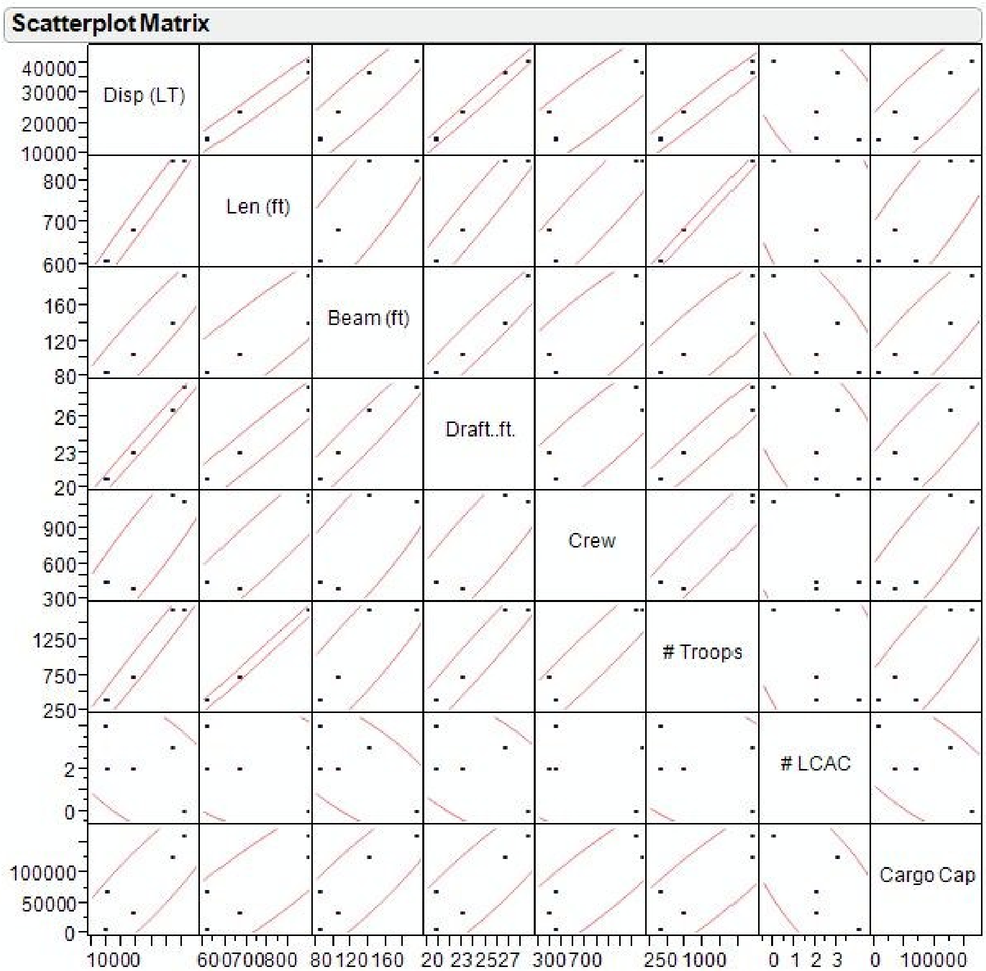


Figure 8. Multi-Collinearity Check Between Factors

## C. BUILDING THE AGGREGATE MODELS

After providing the SEA Department Cost Team with the accepted single variable models discussed in Chapter IV, Part A., Figure 9 displays the variables selected for use by the SEA Department Engineering team at each SWBS level to produce the cost estimate. Of the top three best fits per SWBS level, the SEA Department Cost Team chose the regressors that would be most responsive to the five input parameters of the model, namely: Beam, Cargo Capacity, Crew Size, Troop Size, and LCAC capacity. Displacement, Length, and Draft were eliminated as descriptive variables because they were not important inputs for the SEA Curriculum engineering team. The mean labor hours value is used for SWBS 200, 400, 500, and 700 where regression on labor hours required to complete the particular SWBS level do not meet the required P-value statistic and/or $R^2$ value thresholds.

| SWBS Level | Materiel Variables | Regression Method | Labor Variables | Regression Method |
|---|---|---|---|---|
| 100 | Beam | Linear model | Troops | Power model |
| 200 | Cargo | Linear model | Mean | - |
| 300 | Crew | Power model | Beam | Logarithmic model |
| 400 | Troops | Exponential model | Mean | - |
| 500 | Crew | Logarithmic model | Mean | - |
| 600 | Cargo | Linear model | Troops | Power model |
| 700 | LCAC | Linear model | Mean | - |
| 800 | Beam | Linear model | Crew | Logarithmic model |
| 900 | Beam | Linear model | Troops | Logarithmic model |

Figure 9. Input Parameters for Estimating Materiel Costs and Labor Hours[18]

## D. MODEL VERIFICATION

After building the aggregate model, the model was tested using procurement data from five of the Navy's current amphibious ships and the output costs of the model were

[18] Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Naval Postgraduate School, 2012.

compared with the actual lead ship's cost data. Table 8 displays the input parameters and the results from the analysis. The row titled Total Cost Difference displays the difference between the actual cost of the lead ship and the cost estimated when using the model to be discussed in Section F, Design Costs. Because actual cost data is proprietary in nature, costs reflected in Table 8 are on a relative basis and utilize cost indices. In the case of LHA-6, the aggregate model underestimated the cost by 1.61 percent. The opposite is true for the Harpers Ferry (LSD-49). The model overestimated the cost of the lead ship by 11.5%. Of concern is the total cost difference produced for LPD-17. At 31.66%, the difference is outside the acceptable cost estimation standard of "less than 20%." Further research into the procurement of LPD-17 yields that the USS San Antonio was over budget and behind schedule from its inception.

"The LPD-17 program has experienced considerable cost growth, schedule delays and construction problems, particularly on the earlier ships in the program. The first ship in the program experienced cost growth of about 70%, and later ships in the program were substantially more expensive to build than originally estimated.[19]"

[19]Ronald O'Rourke. *Navy LPD 17 Amphibious Ship Procurement: Background, Issues and Options for Congress* (Washington, D.C., 2011), 4.

| | Whidbey Island | Harpers Ferry | San Antonio | America | Wasp |
|---|---|---|---|---|---|
| Input Parameters | LSD-41 | LSD-49 | LPD-17 | LHA-6 | LHD-1 |
| Number of LCACs | 4 | 2 | 2 | 0 | 3 |
| Cargo (cubic ft) | 5000 | 50700 | 34000 | 160000 | 125000 |
| Number of Crew | 434 | 434 | 388 | 1124 | 1188 |
| Number of Troops | 402 | 402 | 720 | 1687 | 1687 |
| Beam (ft) | 84 | 84 | 105 | 194 | 140 |
| | | | | | |
| Model Output Index | 1.0025 | 1.1149 | 0.6834 | 0.9839 | 1.1850 |
| Total Cost Index Historical | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | |
| Total Index Difference | 0.26% | 11.49% | -31.66% | -1.61% | 18.50% |

Table 9. Historical Lead Ship Data Compared to Costs Produced By Aggregate Model

## E. LEAD SHIP COST ESTIMATES

Given the satisfactory results of the model test conducted in section E, the parameters in Table 9 were utilized to produce a cost estimate for LSD (X) and a larger variant LSD (XB). These parameters were chosen by the SEA Department Engineering Team.

| | **LSD(X)** | **LSD(XB)** |
|---|---|---|
| **Beam** | 90 | 94 |
| **LCACs** | 2 | 2 |
| **Troops** | 400 | 530 |
| **Cargo (cu ft)** | 20000 | 66000 |
| **Crew** | 350 | 380 |

Table 10. Initial Design Parameters Used to Obtain Lead Ship Cost Estimates[20]

The SEA Curriculum cost team utilized a Monte Carlo Simulation to account for variations in costs to adjust the estimates to produce an estimate of the 80th percentile value of the LCCE Cumulative Distribution Function (CDF). This was done in order to ensure compliance with the Weapons Systems Acquisition Reform Act (WSARA) of

20 Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Naval Postgraduate School, 2012.

2009. The WSARA of 2009 requires an 80% confidence level when providing a cost estimate in order to mitigate the risk associated with large procurement projects.[21] Detailed information on the Monte Carlo simulation and its application can be found in Appendix C.

The output cost ranges, based on one standard deviation, for the two simulated alternatives and their respective 80th percentile CDF levels are summarized in Table 11.

| Alternatives | Lower Limit | Upper Limit | 80% CDF |
|---|---|---|---|
| **LSD(X)** | $603.4M | $662.5M | $660.0M |
| **LSD(XB)** | $771.6M | $832.5M | $827.9 M |

Table 11. Results from 100,000 Monte Carlo Simulations for Each Lead Ship Alternative in FY12$[22]

Given the results provided in Table 10, the smaller LSD (X) alternative appears to be the least costly from a strictly procurement perspective. In order to develop the LCCEs, the design costs of the lead ship, the follow on ship costs, and the Operating and Support Costs (O&S) must be calculated and included in an additive fashion.

## F. DESIGN COSTS

Recall that LCCEs consist of three phases: design, procurement, and O&S. Design costs account for the preliminary design as well as any design changes and modifications that need to be made during construction of the first ship. After speaking with industry experts, for the purpose of LSD(X), the estimated design cost to be included into the LCCE is $350M (FY12$).[23]

[21] H.R. 1830--111th Congress: *Weapon Systems Acquisition Reform Act of 2009*. In GovTrack.us (database of federal legislation). Accessed May 7, 2012, http://www.govtrack.us/congress/bills/111/hr1830

[22] Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Naval Postgraduate School, 2012.

[23] Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Naval Postgraduate School, 2012.

## G. FOLLOW-ON SHIP COSTS

With the estimate of the production costs for the lead ships of LSD (X) and a larger variant LSD (XB), we use the learning curve theory to model efficiency gains introduced over the production of the 2nd through 11th ships using the formula below:

$$y_x = Tx^b$$

Where b $= \frac{\ln of\ slope}{\ln of\ 2}$
x = Hull number
y = Unit cost for hull number x
T = Lead ship cost[24]

Initial inputs for the labor learning parameter is set at 95% while the materiel savings parameter was set at 99% as recommended by subject matter experts in the shipbuilding cost estimate field and agreed upon by the SEA Curriculum. This adjustment allows for changes in both parameters to test for sensitivity.[25]

## H. OPERATING AND SUPPORT COSTS

Finally, the O&S costs must be included into the LCCE. In order to do this, we reference the historical O&S data included on the VAMOSC Database (www.vamosc.navy.mil) of NCCA. The O&S costs provided in Table 12 account for the operation and support of one US Amphibious ship for one year and have been adjusted for inflation and converted to FY12 dollars.

---

[24] Naval Postgraduate School. *Unpublished Course Materiel for Course OA4702: Cost Estimation*. Naval Postgraduate School, 2012.

[25] Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Naval Postgraduate School, 2012.

| Historical O&S Data Averages(FY12$M) | | | | |
|---|---|---|---|---|
| | Total O&S | Manpower | Operations | Support |
| LHA-1 Class | $157.8M | $89.4M | $30.8M | $37.6M |
| LHD-1 Class | $157.8M | $86.8M | $28.6M | $42.3M |
| LSD-41 Class | $65.1M | $23.5M | $8.0M | $33.6M |
| LSD-49 Class | $56.9M | $23.7M | $9.6M | $23.6M |
| LPD-4 Class | $64.3M | $29.3M | $14.9M | $20.1M |
| LPD-17 Class | $49.6M | $28.2M | $6.5M | $14.9M |

Table 12. Historical O&S Data for Various US Amphibious Ships[26]

Because LSD(X) is expected to conduct similar operations to the current LSD fleet (LSD-41 and LSD-49), an average of the O&S values is used to calculate the O&S costs for LSD (X). To estimate the alternative larger variant LSD(XB), we add 10% to the average to account for the larger ship size and crew size. Table 13 displays the O&S costs for both variants used in the calculation of the LCCE.

| **Alternatives O&S** | |
|---|---|
| Alternative | FY 12$ (M) |
| LSD(X) | 61.0 |
| LSD(XB) | 67.1 |

Table 13. O&S Cost Estimates for LSD(X) and LSD(XB)[27]

## I. TOTAL LIFE-CYCLE COST ESTIMATE

In order to calculate the total LSD(X) and LSD(XB) LCCE, we add the procurement costs for each additional ship procured with the O&S costs for each ship currently operating. These procurement costs are presented in Table 13 and include the design costs discussed in section F.

[26] Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Naval Postgraduate School, 2012.

[27] Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Naval Postgraduate School, 2012.

| New Construction (FY12$ M) | | |
|---|---|---|
| Hull # | LSD(X) | LSD(XB) |
| 1 | 1010.0 | 1177.9 |
| 2 | 633.0 | 795.2 |
| 3 | 617.8 | 776.8 |
| 4 | 607.3 | 764.1 |
| 5 | 599.3 | 754.4 |
| 6 | 592.8 | 746.6 |
| 7 | 587.4 | 740.0 |
| 8 | 582.8 | 734.4 |
| 9 | 578.8 | 729.5 |
| 10 | 575.2 | 725.2 |
| 11 | 572.0 | 721.3 |

Table 14. New Construction Procurement Costs Calculated Utilizing the Learning Curve Theory Described in Section G

Based on the procurement costs for each ship and the O&S costs for a 30 year period the LCCE for the LSD(X) is $20.37 Billion and $23.42 Billion for LSD(XB). These figures include the assumption that 11 new construction LSD(X) or LSD(XB) class ships are purchased at an interval of one ship every other year during a 22-year period. O&S costs are included annually for each ship in operation. Table 15 provides an example of the LCCE calculation for years 1–7 and Table 16 provides a breakdown of the total LCCE calculations.

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| LSD(X) | 1 | | 2 | | 3 | | 4 |
| Procurement Cost | 1010.00 | | 633.00 | | 617.80 | | 607.30 |
| | 61.00 | 61.00 | 61.00 | 61.00 | 61.00 | 61.00 | 61.00 |
| | | | 61.00 | 61.00 | 61.00 | 61.00 | 61.00 |
| | | | | | 61.00 | 61.00 | 61.00 |
| | | | | | | | 61.00 |
| Cost per Year | 1071.0 | 61.00 | 755.00 | 122.00 | 800.80 | 183.00 | 851.30 |
| Cumulative LCCE | 1071.00 | 1132.00 | 1887.00 | 2009.00 | 2809.80 | 2992.80 | 3844.10 |

Table 15. Example of LCCE Calculation for years 1-7

| | O&S | Procurement | Cumulative LCCE |
|---|---|---|---|
| LSD(X) | $13,412,524,400 | $6,956,541,749 | $20,369,066,149 |
| LSD(XB) | $14,753,776,840 | $8,665,338,641 | $23,419,115,481 |

Table 16. Example of LCCE Calculation Over 30 Year Operating Period

THIS PAGE INTENTIONALLY LEFT BLANK

# V. CONCLUSIONS

## A. SUMMARY

As a summary of key findings of this thesis, a recap of procurement costs estimates for the LSD (X) and LSD(XB) lead ship costs in FY12$ is provided below in Table 17.

| | Design Costs | Procurement | Lead Ship Procurement |
|---|---|---|---|
| LSD(X) | $350M | $660M | $1010M |
| LSD(XB) | $350M | $828.9M | $1177.9M |

Table 17. Lead Ship Procurement Costs for LSD(X) and LSD(XB)

Accounting for learning curve theory and Operating and Support (O&S) costs over a 30 year period generates our LCCE. The LCCE for LSD (X) is $20.37 billion and $23.42 Billion for LSD(XB) in FY$12 dollars and is displayed in Table 18. Included in these figures is the assumption that 11 new construction LSD ships will be purchase at an interval of one ship every other year over a 22-year time frame.

| | O&S | Procurement | Cumulative LCCE |
|---|---|---|---|
| LSD(X) | $13,412,524,400 | $6,956,541,749 | $20,369,066,149 |
| LSD(XB) | $14,753,776,840 | $8,665,338,641 | $23,419,115,481 |

Table 18. Example of LCCE Calculation Over 30 Year Operating Period

Overall, the analysis within this thesis provides the Systems Engineering Analysis Curriculum students with a reliable and justifiable tool to conduct an analysis of alternatives for the LSD fleet recapitalization. These models are simple and effective and allow the user to update the final LCCE as more information on technical composition is made available. By employing the aggregate model provided from this study, the

Systems Engineering Analysis Curriculum students are able to respond to the request from OPNAV N8F by shedding light on the expected costs associated with the procurement of a new LSD fleet.

## B. AREAS FOR IMPROVEMENT

The strength of the aggregate model lies with the fact that a credible and defendable cost estimate can be obtained, given technical parameter characteristics of a new amphibious ship. As displayed in the comparison between LSD(X) and LSD(XB), the aggregate model is sensitive and responsive to minimal parameter changes. This fact allows the model to be an effective tool for decision makers. Conversely, the model was only constructed using five data points and eight technical parameters. The lack of data points and small number of technical parameters led to an unavoidable and unfixable multi-collinearity issue. If more data is not available on the lead ship costs of amphibious ships, one answer may be to look into adding additional technical parameters and removing some of the other parameters that are highly correlated. Another option to obtain more data points and eliminate multi-collinearity may be to include ships classes like carriers, cruisers, destroyers, or auxiliary ships, and assign a scaling factor to account for differences in mission and composition.

## C. RECOMMENDATIONS FOR FUTURE ANALYSIS

Given the results provided by this thesis as well as the SEA Curriculum recommendations for the follow-on LSD, a future study can be conducted when the Navy makes the decision and constructs the follow-on LSD ship. The technical parameters of the new ship can be used as inputs into the model created and described in this thesis. A comparison can be made between the difference of the estimate and the actual procurement cost of the new ship. This difference will give insight as to what parameters should or should not have been included in the model. Because cost estimates are necessary for each and every system acquisition and at every milestone review, further insight and analysis to developing and refining adequate prediction models will always be compulsory.

# APPENDIX A. AGGREGATED MATERIEL COST REGRESSION MODELS

This section shows the details of the nine separate parametric cost models used to build the aggregate cost model for the materiel cost estimate. These models represent the most responsive models for each SWBS level.

| SWBS Level | Materiel Variables | Regression Method | P-Value | $R^2$ Value |
|---|---|---|---|---|
| 100 | Beam | Linear | 0.01 | 0.9 |
| 200 | Cargo Cap | Linear | 0.01 | 0.65 |
| 300 | Crew | Power | 0.04 | 0.79 |
| 400 | Troops | Exponential | 0.03 | 0.84 |
| 500 | Crew | Logarithmic | 0.02 | 0.88 |
| 600 | Cargo Cap | Linear | 0.09 | 0.68 |
| 700 | LCAC | Linear | 0.03 | 0.85 |
| 800 | Beam | Linear | 0.13 | 0.59 |
| 900 | Beam | Linear | 0.002 | 0.98 |

Table 19. Aggregate Materiel Cost Model per SWBS

## A. REGRESSION MODEL 1: MATERIEL COST VS BEAM

Materiel Cost (at 100 SWBS) = - 44,357,995.04 + 618,782.41*Beam (ft)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.950375046 | | | | |
| R Square | 0.903212728 | | | | |
| Adjusted R Square | 0.870950304 | | | | |
| Standard Error | 10897667.7 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 3.32476E+15 | 3.325E+15 | 27.995811 | 0.013171177 |
| Residual | 3 | 3.56277E+14 | 1.188E+14 | | |
| Total | 4 | 3.68104E+15 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | -44357995.04 | 15002893.71 | -2.9566293 | 0.0597055 | |
| Beam..ft. | 618782.4053 | 116947.6309 | 5.2911068 | 0.0131712 | |

Figure 10. Details of Regression Model for 100 SWBS Materiel Cost

## B. REGRESSION MODEL 2: MATERIEL COST VS CARGO CAPACITY

Materiel Cost (at 200 SWBS) = + 14,825,686.83+632.92* Cargo Capacity (CuFt)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.808518 | | | | |
| R Square | 0.6537014 | | | | |
| Adjusted R Square | 0.5382685 | | | | |
| Standard Error | 33961747 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 6.53176E+15 | 6.532E+15 | 5.6630442 | 0.09764294 |
| Residual | 3 | 3.4602E+15 | 1.153E+15 | | |
| Total | 4 | 9.99196E+15 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | 14825687 | 25779405.57 | 0.5750981 | 0.6055234 | |
| Cargo.Capacity | 632.91585 | 265.9628595 | 2.3797152 | 0.0976429 | |

Figure 11. Details of Regression Model for 200 SWBS Materiel Cost

## C. REGRESSION MODEL 3: MATERIEL COST VS. CREW

Materiel Cost (at 300 SWBS) = $10^{2.2142+1.8789(\text{Crew})}$

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.890416 | | | | |
| R Square | 0.7928407 | | | | |
| Adjusted R Square | 0.7237876 | | | | |
| Standard Error | 0.2692641 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 0.83245293 | 0.8324529 | 11.48161 | 0.04282365 |
| Residual | 3 | 0.217509456 | 0.0725032 | | |
| Total | 4 | 1.049962385 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | 2.2141612 | 1.556119239 | 1.4228737 | 0.2499349 | |
| log crew | 1.8789323 | 0.554510446 | 3.3884525 | 0.0428237 | |

Figure 12. Details of Regression Model for 300 SWBS Materiel Cost

## D. REGRESSION MODEL 4: MATERIEL COST VS. TROOPS

Materiel Cost (at 400 SWBS Level) = $10^{6.9371+0.0006(\text{Troops})}$

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.91794529 | | | | |
| R Square | 0.84262355 | | | | |
| Adjusted R Square | 0.79016473 | | | | |
| Standard Error | 0.21270322 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 0.726713538 | 0.7267135 | 16.062573 | 0.0278657 |
| Residual | 3 | 0.135727986 | 0.0452427 | | |
| Total | 4 | 0.862441524 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | 6.93711711 | 0.184567655 | 37.585768 | 4.143E-05 | |
| X..Troops | 0.0006471 | 0.00016146 | 4.0078139 | 0.0278657 | |

Figure 13. Details of Regression Model for 400 SWBS Materiel Cost

## E. REGRESSION MODEL 5: MATERIEL COST VS. CREW

Materiel Cost (at the 500 SWBS level) =- 717,242,801.49+ 290,685,674.30 *log(crew)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.9388732 | | | | |
| R Square | 0.881483 | | | | |
| Adjusted R Square | 0.8419773 | | | | |
| Standard Error | 29882379 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 1.9924E+16 | 1.992E+16 | 22.312814 | 0.01797456 |
| Residual | 3 | 2.6789E+15 | 8.93E+14 | | |
| Total | 4 | 2.2603E+16 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | -717242801 | 172694935 | -4.1532359 | 0.0253724 | |
| log Crew | 290685674 | 61538436.8 | 4.7236441 | 0.0179746 | |

Figure 14. Details of Regression Model for 500 SWBS Materiel Cost

## F. REGRESSION MODEL 6: MATERIEL COST VS. CARGO CAPACITY

Materiel Cost (at 600 SWBS level) =11,504,903.36 + 346.58(Cargo Capacity)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.8217078 | | | | |
| R Square | 0.6752037 | | | | |
| Adjusted R Square | 0.5669382 | | | | |
| Standard Error | 17721631 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 1.95863E+15 | 1.959E+15 | 6.2365578 | 0.08791494 |
| Residual | 3 | 9.42169E+14 | 3.141E+14 | | |
| Total | 4 | 2.9008E+15 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | 11504903 | 13451991.1 | 0.8552565 | 0.4552765 | |
| Cargo Capacity CU f | 346.58291 | 138.782487 | 2.4973101 | 0.0879149 | |

Figure 15. Details of Regression Model for 600 SWBS Materiel Cost

## G. REGRESSION MODEL 7: MATERIEL COST VS. # OF LCAC

Materiel Cost (at the 700 SWBS level) =4,380,774.00 -1,006,470.18 (# LCAC)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.9197818 | | | | |
| R Square | 0.8459986 | | | | |
| Adjusted R Square | 0.7946648 | | | | |
| Standard Error | 735460.05 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 8.91424E+12 | 8.914E+12 | 16.480346 | 0.02694306 |
| Residual | 3 | 1.6227E+12 | 5.409E+11 | | |
| Total | 4 | 1.05369E+13 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | 4380774 | 636927.0874 | 6.8779835 | 0.0062949 | |
| Num LCAC | -1006470.2 | 247923.5325 | -4.0595992 | 0.0269431 | |

Figure 16. Details of Regression Model for 700 SWBS Materiel Cost

## H. REGRESSION MODEL 8: MATERIEL COST VS. BEAM

Materiel Cost (at the 800 SWBS level) =- 17,340,842.70+ 527,018.93(Beam)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.76663252 | | | | |
| R Square | 0.58772543 | | | | |
| Adjusted R Square | 0.45030057 | | | | |
| Standard Error | 23747273.6 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 2.4118E+15 | 2.412E+15 | 4.2767039 | 0.13048936 |
| Residual | 3 | 1.6918E+15 | 5.639E+14 | | |
| Total | 4 | 4.1036E+15 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | -17340843 | 32693034 | -0.530414 | 0.632578 | |
| Beam..ft. | 527018.929 | 254842.362 | 2.0680193 | 0.1304894 | |

Figure 17. Details of Regression Model for 800 SWBS Materiel Cost

## I. REGRESSION MODEL 9: MATERIEL COST VS. BEAM

Materiel Cost (at the 900 SWBS level) = - 45,899,595.03+573,307.33(Beam)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.9877649 | | | | |
| R Square | 0.9756796 | | | | |
| Adjusted R Square | 0.9675727 | | | | |
| Standard Error | 4869688.7 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 2.854E+15 | 2.854E+15 | 120.35298 | 0.0016216 |
| Residual | 3 | 7.1142E+13 | 2.371E+13 | | |
| Total | 4 | 2.9252E+15 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | -45899595 | 6704133.74 | -6.8464617 | 0.006378 | |
| Beam..ft. | 573307.33 | 52258.7557 | 10.970551 | 0.0016216 | |

Figure 18. Details of Regression Model for 900 SWBS Materiel Cost

# APPENDIX B. AGGREGATED LABOR REGRESSION MODELS

This section shows the details of the nine separate parametric cost models used to build the aggregate cost model for the labor hours estimate. These models represent the most responsive models for each SWBS level.

| SWBS Level | Labor Variables | Regression Method | P-Value | $R^2$ Value |
|---|---|---|---|---|
| 100 | Troops | Power | 0.09 | 0.67 |
| 200 | Mean | - | | |
| 300 | Beam | Logarithmic | 0.02 | 0.89 |
| 400 | Mean | - | | |
| 500 | Mean | - | | |
| 600 | Troops | Power | 0.1 | 0.65 |
| 700 | Mean | - | | |
| 800 | Crew | Logarithmic | 0.01 | 0.91 |
| 900 | Troops | Logarithmic | 0.02 | 0.86 |

Table 20. Aggregate Labor Hour Model per SWBS

## A. REGRESSION MODEL 1: LABOR HOURS VS. TROOPS

Labor Hours (at the 100 SWBS level) $=10^{4.4132+0.6606\log(\text{troops})}$

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.8193639 | | | | |
| R Square | 0.6713571 | | | | |
| Adjusted R Square | 0.5618095 | | | | |
| Standard Error | 0.1667906 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 0.170487913 | 0.1704879 | 6.1284497 | 0.0896208 |
| Residual | 3 | 0.08345728 | 0.0278191 | | |
| Total | 4 | 0.253945193 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | 4.4131573 | 0.778470594 | 5.6690096 | 0.0108723 | |
| log Num Troops | 0.6605682 | 0.266834714 | 2.4755706 | 0.0896208 | |

Figure 19. Details of Regression Model for 100 SWBS Labor Hours

## B. REGRESSION MODEL 2: LABOR HOURS VS. BEAM

Labor Hours (at the 300 SWBS level) = - 8,145,294.16+ 4,436,844.02*log(beam)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.943998 | | | | |
| R Square | 0.8911322 | | | | |
| Adjusted R Square | 0.8548429 | | | | |
| Standard Error | 279880.01 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 1.92357E+12 | 1.924E+12 | 24.556358 | 0.01577455 |
| Residual | 3 | 2.34998E+11 | 7.833E+10 | | |
| Total | 4 | 2.15857E+12 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | -8145294.2 | 1849075.624 | -4.4050628 | 0.0216964 | |
| log beam | 4436844 | 895348.6573 | 4.9554372 | 0.0157746 | |

Figure 20. Details of Regression Model for 300 SWBS Labor Hours

## C. REGRESSION MODEL 3: LABOR HOURS VS. TROOPS

Labor Hours (at the 600 SWBS level) $=10^{2.84+1.12\log(\text{troops})}$

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.8078277 | | | | |
| R Square | 0.6525855 | | | | |
| Adjusted R Square | 0.5367807 | | | | |
| Standard Error | 0.2958864 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 0.4933566 | 0.4933566 | 5.6352193 | 0.09816063 |
| Residual | 3 | 0.26264635 | 0.0875488 | | |
| Total | 4 | 0.75600296 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | 2.8390904 | 1.38100671 | 2.0558122 | 0.1320252 | |
| log Num Troops | 1.1237024 | 0.47336474 | 2.3738617 | 0.0981606 | |

Figure 21. Details of Regression Model for 600 SWBS Labor Hours

## D. REGRESSION MODEL 4: LABOR HOURS VS. CREW

Labor Hours (at the 800 SWBS level) = - 24,430,121.22+ 9,778,347.63*log(crew)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.953709 | | | | |
| R Square | 0.9095609 | | | | |
| Adjusted R Square | 0.8794145 | | | | |
| Standard Error | 864442 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 2.25459E+13 | 2.255E+13 | 30.171483 | 0.011872436 |
| Residual | 3 | 2.24178E+12 | 7.473E+11 | | |
| Total | 4 | 2.47877E+13 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | -24430121 | 4995745.294 | -4.8901855 | 0.0163567 | |
| log Crew | 9778347.6 | 1780193.241 | 5.4928574 | 0.0118724 | |

Figure 22. Details of Regression Model for 800 SWBS Labor Hours

## E. REGRESSION MODEL 5: LABOR HOURS VS. TROOPS

Labor Hours (at the 900 SWBS level) = - 11,271,570.35 + 4,872,618.37*log(troops)

| *Regression Statistics* | | | | | |
|---|---|---|---|---|---|
| Multiple R | 0.9262458 | | | | |
| R Square | 0.8579312 | | | | |
| Adjusted R Square | 0.810575 | | | | |
| Standard Error | 715573.1 | | | | |
| Observations | 5 | | | | |
| | | | | | |
| ANOVA | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* |
| Regression | 1 | 9.2765E+12 | 9.276E+12 | 18.116533 | 0.02377663 |
| Residual | 3 | 1.5361E+12 | 5.12E+11 | | |
| Total | 4 | 1.0813E+13 | | | |
| | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | |
| Intercept | -11271570 | 3339832.87 | -3.3748905 | 0.0432542 | |
| log Num Troops | 4872618.4 | 1144787.42 | 4.2563521 | 0.0237766 | |

Figure 23. Details of Regression Model for 900 SWBS Labor Hours

# APPENDIX C. MONTE CARLO SIMULATIONS

Monte Carlo simulation techniques are used in this thesis for estimating uncertainty for cost of the lead ships. Monte Carlo simulations are computational algorithms that rely on repeated random sampling to compute their results. These simulations were used to account for variations in the design, construction, and cost estimating processes. The following documentation was provided by the Systems Engineering Analysis Curriculum Students on the use of Monte Carlo Simulations[28]:

> Introduction: The American Association of Cost Engineers (AACE) defines cost engineering as "that area of engineering practice where engineering judgment and experience are utilized in the application of scientific principles and techniques to the problems of cost estimation, cost control, and profitability." (AACE International, 2011) Cost estimation essentially uses the plan of a project and maps it to a dollar value by applying appropriate costs to the quantities identified in the plan, and in this case, gives insight into how much a lead ship would cost. However, it must be noted that figures derived via this process are predictions at best due to the fundamentally uncertain nature of cost estimation. This uncertainty stems from the following two categories (Fisher, 1962):
>
> Requirements Uncertainty: This refers to the variability in cost estimates due to changes in the configuration of the system being estimated. As an example, suppose that, at present, the analysis of system configurations for each ship suggested an optimal loading capacity of 1000 troops. While valid under present day circumstances, this requirement may change further down the acquisition/manufacturing process, thereby rendering cost estimates incorrect. While the example cited specifications of the ship, this uncertainty may also apply to hardware characteristics and/or operational concepts.
>
> Cost-Estimating Uncertainty: This refers to variations in cost estimates of a system even though the original configuration remains unchanged. This variation may arise from errors in the data base, errors or inappropriateness of cost estimating techniques, insufficient data for building the costing model, and the inherent uncertainty of the cost model, as identified, for example in the statistics such as Standard Error of the Estimates (SEE).

[28] Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Naval Postgraduate School, 2012.

The relationship between the system cost uncertainty and its sources can be depicted using the display in Figure 24.

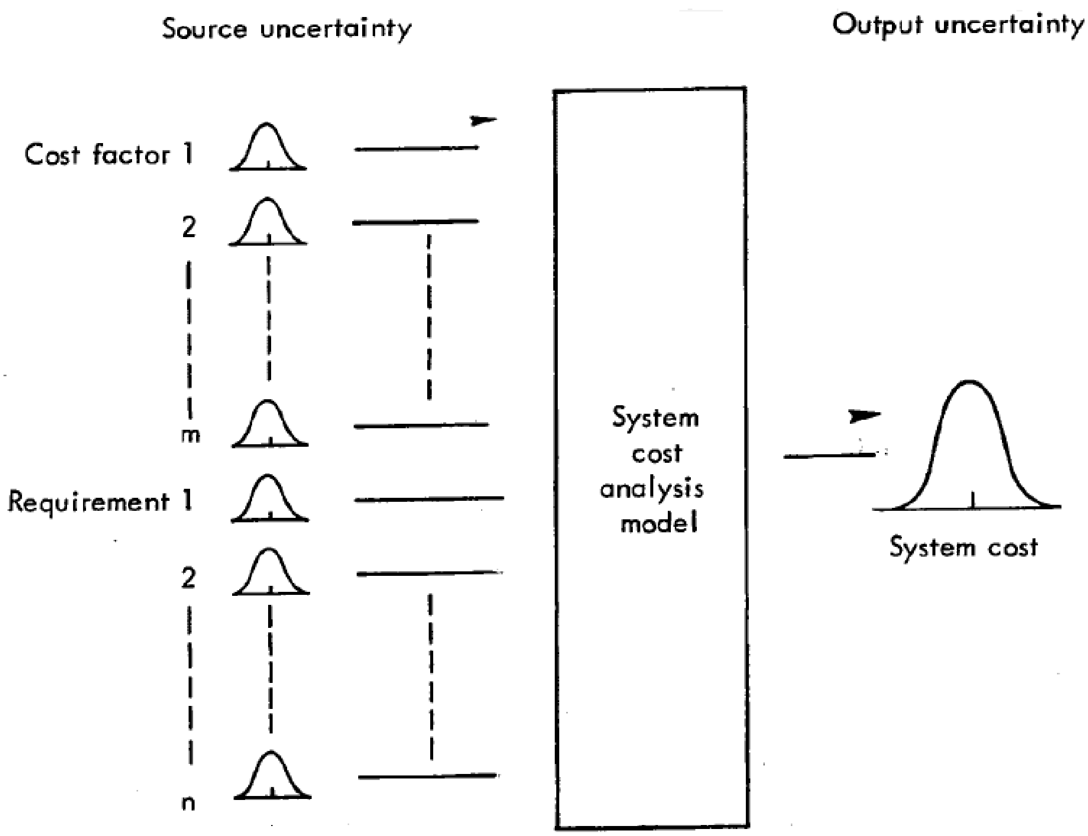


Figure 24. Relation of System Cost Uncertainty to Source Uncertainty (From Dienemann, 1966)

Associated with each cost input is a probability distribution to reflect its uncertainty. Given that each input parameter is described with a probability distribution, the distribution is then treated as a theoretical population from which random samples are taken, and which are used to develop an aggregated LCCE distribution. This technique is referred to as Monte Carlo simulation.

Methodology: A Monte Carlo simulation was run for each cost component, i.e. for materiel costs and for labor costs. The steps are detailed below.

a. Identifying Probability Distribution. The first step involves identifying the parameters of a suitable probability distribution. Given the limited data points in creating the regression model for each SWBS level, it was decided that using a Triangle distribution[29] would be appropriate.

b. Deriving Parameters. As mentioned in Section 5, each SWBS level had a regression model built, to estimate either materiel costs or labor hours, as a function of only one regressor. Let this model be termed *f(x)*. The range of this regressor was obtained from the data set and three values in this range were passed through the regression model to obtain the parameters for the Triangle distribution, namely, the lowest value over the range *a* to obtain parameter *f(a)*, the highest value over the range *c* to obtain parameter *f(c)* and the most likely value *b* to obtain parameter *f(b)*. Fig 25 illustrates this procedure.

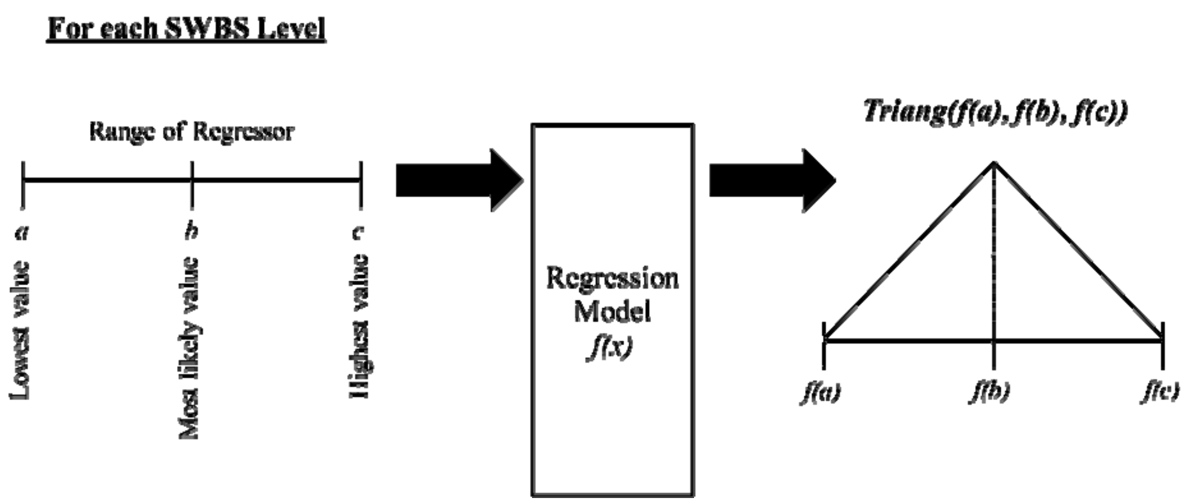


Figure 25. Procedure for Derivation of Parameters

---

[29] *Tri (a, b, c)* where *a* corresponds with the lowest value, *c* corresponds with the highest value and *b* corresponds with the most likely value.

## A. LSD(X) ALTERNATIVE

The following methodology applies to estimates for alternatives that involve utilizing a newly designed ship hull form for the project. These alternatives that use this include: LSD(X) and LSD(XB). The ranges of the regressors used as input parameters to estimate the cost of the LSD(X) Small Variant are shown in Table 21.

| Regressor | Lowest Value | Most Likely Value | Highest Value |
|---|---|---|---|
| **Beam** | 81 | 90 | 99 |
| **LCACs** | 1 | 2 | 3 |
| **Troops** | 340 | 400 | 460 |
| **Cargo (cuft)** | 17000 | 20000 | 23000 |
| **Crew** | 298 | 350 | 403 |

Table 21. Range of Values for Regressors – LSD(X)

The final probability distributions for materiel costs and labor hours are shown below.

| SWBS Level | Regressor | Lowest Value | Most Likely Value | Highest Value |
|---|---|---|---|---|
| 100 | Beam | 5763380 | 11332421 | 16901463 |
| 200 | Cargo | 25585255 | 27484003 | 29382750 |
| 300 | Crew | 7295348 | 9869447 | 12863317 |
| 400 | Troops | 14359267 | 15702126 | 17170568 |
| 500 | Crew | 1976422 | 22281333 | 40082053 |
| 600 | Cargo | 17396813 | 18436561 | 19476310 |
| 700 | LCAC | 3374304 | 2367834 | 1361364 |
| 800 | Beam | 25347691 | 30090861 | 34834031 |
| 900 | Beam | 538299 | 5698065 | 10857831 |

Table 22. Probability Distributions for Materiel Costs – LSD(X)

| SWBS Level | Regressor | Lowest Value | Most Likely Value | Highest Value |
|---|---|---|---|---|
| 100 | Troops | 1217227 | 1355175 | 1486245 |
| 200 | Mean | 307295 | 307295 | 307295 |
| 300 | Beam | 322356 | 525375 | 709028 |
| 400 | Mean | 453541 | 453541 | 453541 |
| 500 | Mean | 2243576 | 2243576 | 2243576 |
| 600 | Troops | 482747 | 579471 | 678013 |

| | | | | |
|---|---|---|---|---|
| 700 | Mean | 50235 | 50235 | 50235 |
| 800 | Crew | -236374 | 446661 | 1045457 |
| 900 | Troops | 1063360 | 1407275 | 1703032 |

Table 23. Probability Distributions for Labor Hours – LSD(X)

Simulation Results. 100,000 simulations were run for each cost component with the following results:

a. Materiel Costs. The simulations resulted in a mean of \$142.6M with a standard deviation of \$8.7M This resulted in a range of between \$133.8M and \$151.3M based on one standard deviation. The results of the Monte Carlo simulation are shown in Fig 26. The corresponding 80% CDF level is approximately \$150M.

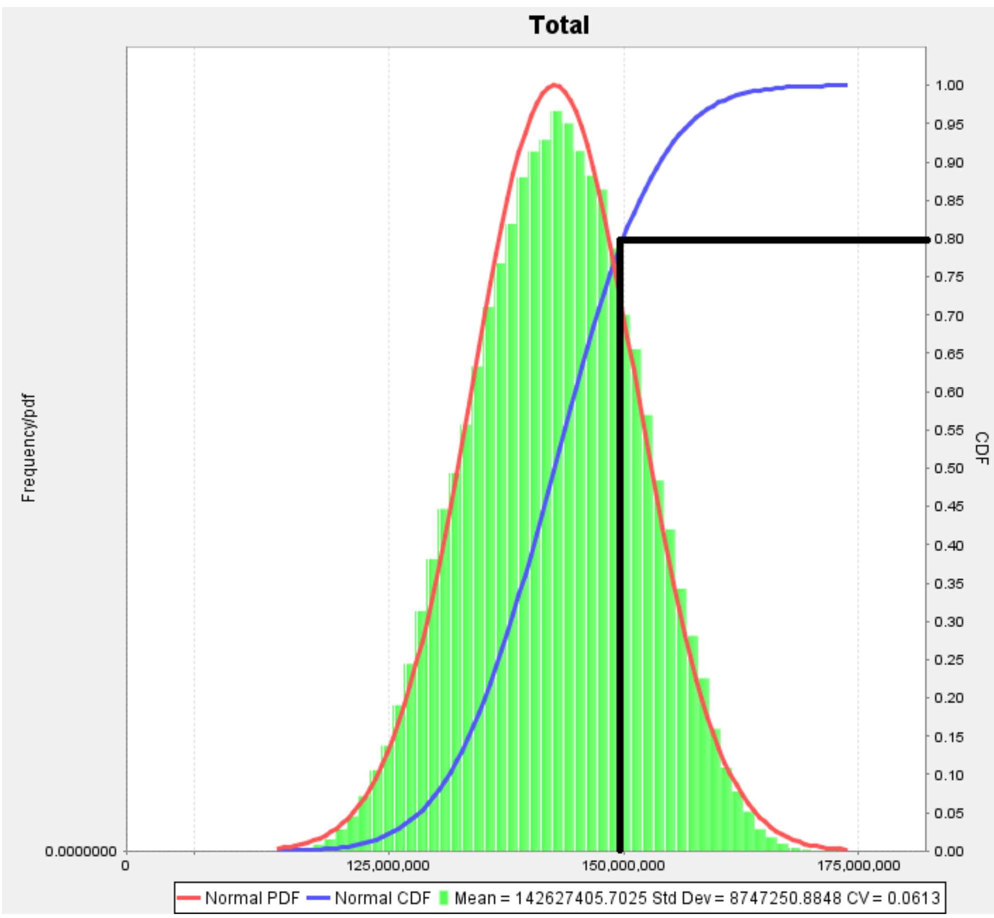


Figure 26. Results of Monte Carlo Simulation for Materiel Costs – LSD(X)

b. Labor Hours. The simulations resulted in a mean 7.3M hours, with a standard deviation of 310,118 hours. After factoring in the recommended labor rate of $67.02 per hour, the range for the total cost of labor was between $469.6M and $511.1M based on one standard deviation. The results of the Monte Carlo simulation are shown in Fig 27. The corresponding 80% CDF level is approximately 7.6M hours, or $510.0M after factoring in labor rates.

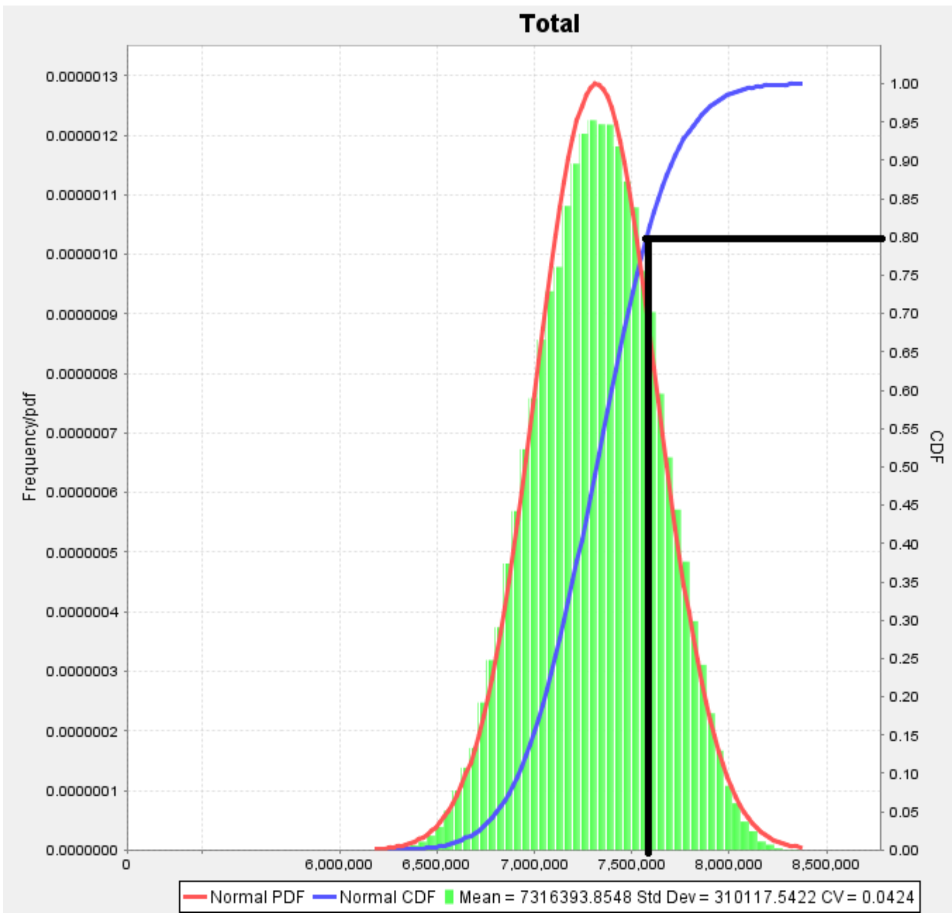


Figure 27. Results of Monte Carlo Simulation for Labor Hours – LSD(X)

Monte Carlo simulation yielded a total cost range of between $603.4M and $662.5M based on one standard deviation for the LSD(X) Small variant. The 80% CDF level is $660M.

## B. LSD(XB)THE LARGER NEW CONSTRUCTION ALTERNATIVE

The ranges of the regressors used as input parameters to estimate the cost of the LSD(XB) Variant are shown in Table 24.

| Regressor | Lowest Value | Most Likely Value | Highest Value |
|---|---|---|---|
| **Beam** | 84.6 | 94 | 103.4 |
| **LCACs** | 1 | 2 | 3 |
| **Troops** | 451 | 530 | 610 |
| **Cargo (cuft)** | 56100 | 66000 | 75900 |
| **Crew** | 323 | 380 | 437 |

Table 24. Range of Values for Regressors – LSD(XB)

The final probability distributions for materiel costs and labor hours are shown below.

| SWBS Level | Regressor | Lowest Value | Most Likely Value | Highest Value |
|---|---|---|---|---|
| 100 | Beam | 7990996 | 13807551 | 19624106 |
| 200 | Cargo | 50332263 | 56598130 | 62863996 |
| 300 | Crew | 8487560 | 11518606 | 14977766 |
| 400 | Troops | 16941846 | 19058201 | 21470896 |
| 500 | Crew | 12146426 | 32663333 | 50307325 |
| 600 | Cargo | 30948204 | 34379375 | 37810545 |
| 700 | LCAC | 3374304 | 2367834 | 1361364 |
| 800 | Beam | 27244959 | 32198937 | 37152915 |
| 900 | Beam | 2602205 | 7991294 | 13380383 |

Table 25. Probability Distributions for Materiel Costs – LSD(XB)

| SWBS Level | Regressor | Lowest Value | Most Likely Value | Highest Value |
|---|---|---|---|---|
| 100 | Troops | 1466972 | 1632027 | 1790843 |
| 200 | Mean | 307295 | 307295 | 307295 |
| 300 | Beam | 406148 | 609166 | 792819 |
| 400 | Mean | 453541 | 453541 | 453541 |
| 500 | Mean | 2243576 | 2243576 | 2243576 |
| 600 | Troops | 663124 | 794998 | 931048 |
| 700 | Mean | 50235 | 50235 | 50235 |
| 800 | Crew | 105733 | 795900 | 1389424 |
| 900 | Troops | 1661219 | 2002786 | 2300279 |

Table 26. Probability Distributions for Labor Hours – LSD(XB)

THIS PAGE INTENTIONALLY LEFT BLANK

# LIST OF REFERENCES


Commander US 7th Fleet. (2011). *Essex Embarks Japan Maritime Self-Defense Force Officer for Humanitarian Aid and Disaster Relief Coordination*, Retrieved October 12,2011, http://www.c7f.navy.mil/news/2011/03-march/066.htm.

Congressional Budget Office. (2011a). *An Analysis of the Navy's Amphibious Warfare Ships for Deploying Marines Overseas*. Washington D.C.

Congressional Budget Office. (2011b). *An Analysis of the Navy's Fiscal Year 2012 Shipbuilding Plan*. Washington D.C.

Devore, Jay. *Probability and Statistics for Engineering and the Sciences 7th Edition*. Brooks/Cole, Belmont, CA. 2007

Dienemann, P.F. (1966) Estimating Cost Uncertainty Using Cost Monte Carlo Techniques. RAND Corporation, Santa Monica, CA.

Doehring, T. (2012) *Unofficial U.S. Navy Site*, Accessed January 21, 2012. http://www.navysite.de

Fisher, G. F. (1962) *A Discussion of Uncertainty in Cost Analysis* RAND Corporation, Santa Monica, CA

Global Security Organization. (2011a). *Amphibious Assault Ships*. Retrieved October 12,2011. http://www.globalsecurity.org/military/systems/ship/lha-1.htm

Global Security Organization. (2011b) *Landing Platform Dock.* Retrieved October 12, 2011. http://www.globalsecurity.org/military/systems/ship/lpd-17.htm

Global Security Organization (2011c), *LSD 41*. Retrieved October 12, 2011. http://www.globalsecurity.org/military/systems/ship/lsd-41.htm

H.R. 1830--111th Congress. (2009). *Weapon Systems Acquisition Reform Act of 2009*. In GovTrack.us (database of federal legislation). Retrieved May 7, 2012, http://www.govtrack.us/congress/bills/111/hr1830

Jane's Fighting Ships. (2011). *Amphibious Assault Ships.* Retrieved October 12, 2011, http://www4.janes.com/

Kaluzny, B. L. (2011) . *An Application of Data Mining Algorithms for Shipbuilding Cost Estimation.* Defence Research & Development Canada Centre for Operational Research & Analysis.

Loftus, K. J. (1999) *A Parametric Cost Model for Estimating Acquisition Costs of Conventional U.S. Navy Surface Ships.* Master's Thesis, Operations Research Department, Naval Postgraduate School, Monterey, CA.

Naval Postgraduate School. (2012). *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment.* Monterey, CA.

Naval Postgraduate School. (2012). *Unpublished Course Materiel for Course OA4702: Cost Estimation.* Monterey, California.

Naval Sea Systems Command Cost Engineering and Industrial Analysis Group. (2008). *Overview of Cost Estimating Unpublished Presentation*. NAVSEA. Washington DC.

O'Rourke, R. (2011). *Navy LPD 17 Amphibious ship Procurement: Background, Issues and Options for Congress*. Washington, D.C.

RAND Corporation. (2006). *Why Has the Cost of Navy Ships Risen?* Santa Monica, CA.

Straubinger, E.K., Curran, W. C., Fighera V. L. (1983). *Fundamentals of Naval Surface Ship Estimating*. Naval Engineers Journal, 95(3), 127-143.

USS Whidbey Island . (2011). *USS Whidbey Island (LSD 41) Official Webpage*. Accessed October 12, 2011, http://navysite.de/ships/lsd41.htm.

# INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Dr. Daniel Nussbaum
   Naval Postgraduate School
   Monterey, California

4. LtCol Gregory Mislick, USMC (Ret)
   Naval Postgraduate School
   Monterey, California

5. Clifford Whitcomb
   Naval Postgraduate School
   Monterey, California